

The physical properties of extrasolar planets

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Abstract. Tremendous progress in the science of extrasolar planets has been achieved since the discovery of a Jupiter orbiting the nearby Sun-like star 51 Pegasi in 1995. Theoretical models have now reached enough maturity to predict the characteristic properties of these new worlds, mass, radius, atmospheric signatures, and can be confronted with available observations. We review our current knowledge of the physical properties of exoplanets, internal structure and composition, atmospheric signatures, including expected biosignatures for exo-Earth planets, evolution, and the impact of tidal interaction and stellar irradiation on these properties for the short-period planets. We discuss the most recent theoretical achievements in the field and the still pending questions. We critically analyse the different solutions suggested to explain abnormally large radii of a significant fraction of transiting exoplanets. Special attention is devoted to the recently discovered transiting objects in the overlapping mass range between massive planets and low-mass brown dwarfs, stressing the ambiguous nature of these bodies, and we discuss the possible observable diagnostics to identify these two distinct populations. We also review our present understanding of planet formation and critically examine the different suggested formation mechanisms. We expect the present review to provide the basic theoretical background to capture the essential of the physics of exoplanet formation, structure and evolution, and the related observable signatures.

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1. Introduction

The end of the twentieth century saw a revolution in our knowledge of planetary systems. The discovery of the first extrasolar planet in 1995 marked the beginning of a modern era and a change of our perception of planets. The discoveries continue apace and reveal an extraordinary diversity of planetary systems and exoplanet physical properties, raising new questions in the field of planetary Science. More than 400 exoplanets have now been unveiled by radial velocity measurements, microlensing experiments and photometric transit observations. They span a wide range of masses from a few Earth masses to a few tens of Jupiter masses ([1]). The realm of terrestrial exoplanets starts to open its doors with the lightest known exoplanet, GJ 581e, detected by radial velocity and having a mass $M \sin i = 1.9$ Earth masses (M_{\oplus}) ([2]). At the opposite end of the mass range, an ambiguity appears on the nature of newly discovered objects. It now becomes clear that giant planets and brown dwarfs share a common mass range, likely between a few Jupiter masses and several tens of Jupiter masses.

Coincidentally, the first brown dwarf was discovered at nearly the same time as the first exoplanet, but with different technologies and observational strategies. Identifying these two astrophysical body populations remains an open issue. Brown dwarfs are supposed to form like stars through the gravitational fragmentation of a molecular cloud while planets are thought to form in a protoplanetary disk subsequently to star formation. A brown dwarf is an object unable to sustain stable hydrogen fusion because of the onset of electron degeneracy in its central region. This definition provides a theoretical upper limit for their mass: objects below ~ 0.07 solar masses (M_{\odot}) or 70 Jupiter masses (M_{Jup}) belong to the brown dwarf realm ([3]). But brown dwarfs with increasingly small masses have now begun to be discovered, reaching masses characteristic of our solar system gaseous giants. In parallel, planet hunters have discovered massive objects around central stars with orbital properties characteristic of planetary systems. They have been faced with an unprecedented difficulty to name their favourite object and the community even called into question the definition of a planet ([4]). This uncertainty about how to call these objects yields some sterile, semantic debates which shed more confusion than light.

On a theoretical point of view, the physical properties of giant planets and brown dwarfs can be described within similar theoretical frameworks, the two families of objects being closely related in terms of atmospheric and interior properties. Because of different formation processes, distinctions are expected concerning their composition and content of heavy elements and these differences must be taken into account in theoretical models. But clearly, the nascent theory for exoplanets has inherited from our knowledge of the Solar System planets, mostly developed during the past century, and from the recent progress performed in the modelling of brown dwarfs. Therefore, the description of the physical properties of exoplanets is built on a combination of our knowledge in planetary and stellar science.

The aim of our review is to present the status of the modern theory describing

atmospheric, interior and evolutionary properties of exoplanets, as well as their formation mechanisms. Most exoplanets yet detected through radial velocity and photometric transits are giant planets, characterised by the presence of a gaseous envelope mostly made of hydrogen and helium ([1]). Crucial constraints on their structure are revealed by photometric transit and Doppler follow-up techniques, which provide a measure of their mass and radius. Information on the mean density and bulk composition of several exoplanets is thus now available, drastically extending the knowledge of planetary structures restricted till recently to our four giant planets. Atmospheric properties of exoplanets also start to be measured and first constraints on temperature structure, composition and dynamics are now available. At dawn of their discovery, no observational constraints on Earth-like exoplanets are yet available. Our review is thus essentially devoted to giant planets and we will only briefly describe the first theoretical efforts devoted to the description of terrestrial exoplanets.

The review is organised as follows. As introductory sections to the field, §2 and §3 provide brief overviews of solar and extra-solar system planets and of our current understanding of planet formation, respectively. Interior structure properties of terrestrial to jovian planets are described in §4, while §5 is devoted to their atmospheric properties. Evolutionary properties, describing planet cooling and contraction history and the mass-radius relationship are presented in §6. Tidal effects and star-planet interactions are examined in §7. Current observational constraints (*e.g* transiting radii, planetary light detection) are analysed in §8. Finally, some future advancements expected in the field are discussed in §9.

2. A brief overview of observations

In this section, we present observed properties of Solar and extra-solar planets which are relevant for the understanding of exoplanet physical properties. For more details, we invite the reader to refer to the reviews by [5, 6] on Solar System giant planets and by [1] on statistical properties of exoplanets.

2.1. Lessons from our Solar System

The understanding of planetary structure starts with the extensive works conducted on our Solar System giant planets. Important constraints on interior structures of our four giant planets are provided by measurement of their gravity field through analysis of the trajectories of the space missions Voyager and Pioneer. Our giant planets are fast rotators, with rotation periods of about 10 hours for Jupiter and Saturn, and about 17 hours for Neptune and Uranus. Rotation modifies the internal structure of a fluid body and yields departure of the gravitational potential from a spherically symmetric potential. Within the framework of a perturbation theory largely developed for rotating stars and planets, sometimes referred to as the theory of figures ([7]), the gravitational potential can be expressed in terms of even (for axysymmetric bodies)

Table 1 Interior properties of Jupiter and Saturn according to [11]. M_{core} is the mass of the rocky/icy core; M_Z the mass of heavy elements in the envelope; $M_Z^{\text{tot}} = M_{\text{core}} + M_Z$ the total mass of heavy elements; Z/Z_{\odot} is the ratio of heavy elements in the planet to that in the Sun.

	Jupiter (317.8 M_{\oplus})	Saturn (95.1 M_{\oplus})
M_{core}	0 - 11 M_{\oplus}	9 - 22 M_{\oplus}
M_Z	1 - 39 M_{\oplus}	1 - 8 M_{\oplus}
M_Z^{tot}	8 - 39 M_{\oplus}	13 - 28 M_{\oplus}
Z/Z_{\odot}	1 - 6	6 - 14

Legendre Polynomials and gravitational moments J_{2n} . The latter are related to the inner density profile of the rotating object. Measurements of J_2 , J_4 and J_6 for the four giant planets yield stringent constraints on their inner density profile. An abundant literature exists on the application of the theory of figures to our four giant planets and most models are based on the so-called three-layer model ([8]). For Jupiter and Saturn, models assume that the planetary interior consists of a central rocky and/or icy core[†], an inner ionised helium and hydrogen envelope, and an outer neutral He and molecular H_2 envelope (see [10, 5] and references therein). Table 1 summarizes the results of a detailed analysis performed by [11], taking into account uncertainties on the equation of state for hydrogen at high density. More recent models for Jupiter were derived by [12, 13] based on improved equations of state for H and He derived from first-principles methods. They however reach contradictory conclusions. While [13] essentially agree with the results of [11], [12] find a larger core, of about 16 M_{\oplus} , and exclude a solution without a core. These two recent works illustrate the remaining uncertainties on planetary modelling and on equations of state of matter under conditions characteristic of giant planet interiors (see §4.1).

The lighter giant planets, Uranus and Neptune, are more enriched in heavy elements than their massive companions. A wide variety of models can match the mass/radius of these planets. Three-layer models with a central rocky core, an ice layer and an outer H/He envelope suggest an overall composition of 25% by mass of rocks, 60-70% of ices and 5-15% of gaseous H/He ([14]). Other solutions exist, as suggested by [15], assuming, instead of a pure ice second layer, a mixture of ice, rock and gas (see Table 2). According to recent estimates, an upper limit for the H/He mass fraction is about 5 M_{\oplus} for Uranus and 4.7 M_{\oplus} for Neptune if only rock and H/He are present ([16]).

Interestingly enough, models for Uranus assuming that each layer is homogeneous with an adiabatic temperature profile fail to reproduce the gravitational moments. An interesting solution for this problem, suggested by [15], is to assume that some parts of

[†] The term "rock" usually refers to silicates (Mg-, Si- and O-rich compounds) and the term "ice" involves a mixture of volatiles dominantly composed of water, with traces of methane and ammonia.

Table 2 Examples of interior composition for Uranus and Neptune according to [15]. The models assume (i) one rock layer, (ii) one layer composed of a mixture of rock, ice and H/He and (iii) a third layer of H/He. M_{rock} , M_{ice} and $M_{\text{H/He}}$ are the total masses of rock, ice and H/He respectively.

	Uranus (14.5 M_{\oplus})	Neptune (17.1 M_{\oplus})
M_{rock}	3.7 M_{\oplus}	4.2 M_{\oplus}
M_{ice}	9.3 M_{\oplus}	10.7 M_{\oplus}
$M_{\text{H/He}}$	1.5 M_{\oplus}	2.2 M_{\oplus}

the layers are not homogeneously mixed. In the presence of a persistent molecular weight gradient, convection can be confined in numerous homogeneous layers separated by thin diffusive interfaces. This process, known as layered or double diffusive convection, provides a solution to reproduce the observed gravitational moments in Uranus ([15]). We will see in section 8.1 that this process may also be relevant for extra-solar transiting planets.

The analysis of the atmospheric composition of our giant planets also shows a significant enrichment in heavy elements. Abundances of several elements (C, N, S, Ar, Kr, Xe) have been measured in situ by the Galileo probe for Jupiter and they show a global enrichment compared to solar values of about a factor 3 ([17, 6]). For Saturn, spectroscopic detections of methane and ammonia suggest significant enrichment of C (about a factor 6 [17]) and N (about a factor 2 [6]), although with large uncertainties for the latter element. For Uranus and Neptune, carbon is significantly enriched, with large factors > 20 ([17]) while the abundance of N/H is comparable to that of Jupiter and Saturn ([6]).

The interior and atmospheric properties of our giant planets bear important consequences on our general perception of planetary structure. The observational evidences that our giant planets are enriched in heavy material support our general understanding of planet formation (see §3) and guide the development of a general theory for exoplanets.

2.2. Observed properties of exoplanets

The description of exoplanet physical properties must encompass the wide variety of planetary masses and orbital separations yet discovered, as illustrated in Fig. 1. About 30% of exoplanets have an orbital separation a less than 0.1 AU. Irradiation effects from their parent star must thus be accounted for for a correct description of their structural and evolutionary properties. Another compelling property of exo-planetary systems is the correlation between planet-host star metallicity[‡] and frequency of planets. The

[‡] The metallicity is defined as the mass fraction of all chemical elements heavier than helium.

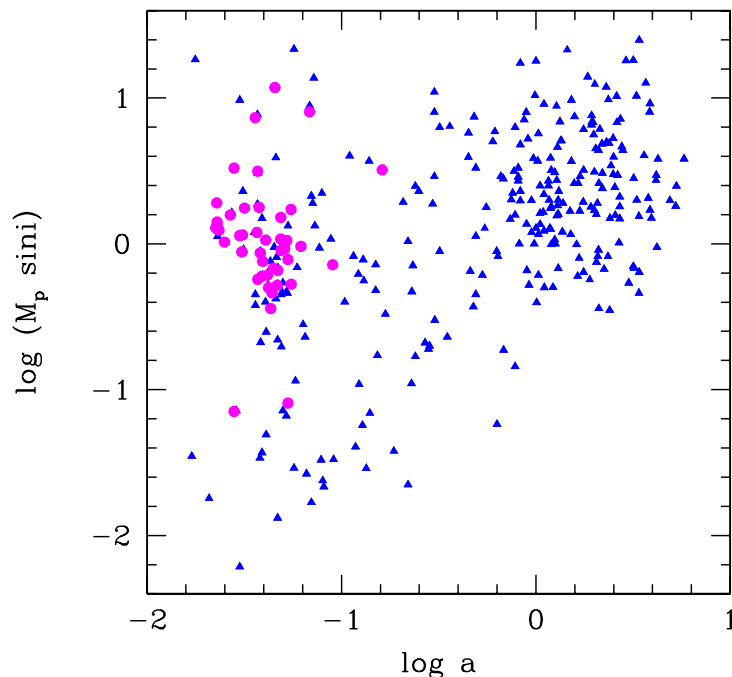


Figure 1 Mass of known extra-solar planets (in M_\oplus) as a function of orbital distance (in AU). Triangles are planets detected by radial velocity surveys (from the web site of J. Schneider: <http://exoplanet.eu/catalog-RV.php>) and solid circles are transiting planets (from the web site of F. Pont: <http://www.inscience.ch/transits/>).

probability of finding giant planets is a strong function of the parent star metallicity, indicating that an environment enriched in heavy material favours planet formation ([1]). This correlation, however, is not observed for light Neptune-mass planets ([1]), although the statistics is still poor. About twenty of these light planets have yet been discovered ([1]). These trends provide clues about their formation process, as discussed in §3.

Crucial information on interior structure and bulk composition of exoplanets are unveiled by objects transiting in front of their parent star. About sixty of these planets have yet been detected, revealing an extraordinary variety in mean planetary densities and composition. As illustrated in Fig. 2, some exoplanets are significantly denser, thus more enriched in heavy material than our own giant planets. One of the most remarkable discovery is the Saturn mass planet HD 149026b with such a small radius that more than $70 M_\oplus$ of heavy material is required to explain it ([18]). This discovery raises the question of the formation process of planets with such a large amount of heavy material. More importantly, it tells us that exoplanets, like our Solar System planets,

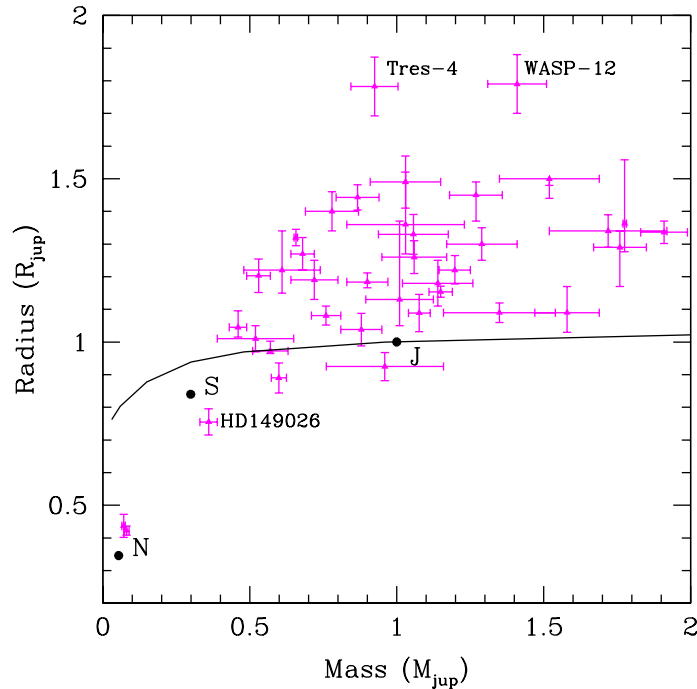


Figure 2 Mass - radius diagram for transiting planets. The positions of Jupiter, Saturn and Neptune are indicated by full circles. The curve shows theoretical predictions for solar metallicity objects $Z = 2\%$ (models from [19]). Note that the weak enrichment in heavy material of Jupiter ($Z \sim 10\%$, see Table 1) is counterbalanced by the effect of rotation (see §2.1), and the radius of Jupiter is coincidentally reproduced by solar composition models. Data taken from the web site of F. Pont: <http://www.inscience.ch/transits/>.

may contain large amounts of heavy material, supporting our current understanding of planetary formation (see §3).

Another puzzling property revealed by Fig. 2 is the abnormally large radius of a significant fraction of transiting planets. Oddly enough, the very first transiting planet ever discovered, HD209458b ([20]), was found with a large radius which still challenges our understanding of planetary structure. At the time of this writing, the two most inflated exoplanets known are TRES-4b, with a radius $R_p = 1.78R_{\text{Jup}}$ and a mass $M_p = 0.9 M_{\text{Jup}}$ ([21]) and WASP-12b, with $R = 1.79R_{\text{Jup}}$ and $M_p = 1.4 M_{\text{Jup}}$ ([22]). These observations indicate that new mechanisms are required to inflate close-in planets. Whether these mechanisms are peculiar, operating only under very specific conditions and planetary system configurations, or whether basic physics is missing in the modelling of close-in giant planets are still open questions. Several mechanisms have been proposed since the discovery of HD209458, but no firm answer has been obtained for now. In this review, we will present the main proposed mechanisms and discuss their

status (§8.1).

3. Planet formation

3.1. Core-accretion model

The presently most widely accepted scenario for giant planet formation is the so-called core-accretion model [23, 24]. In this model, solid cores grow oligarchically in the surrounding nebula by accreting small planetesimals[§], located within the protoplanet's zone of gravitational influence, called the feeding zone, which extends over a few Hills radii ($R_H = a(M_p/3M_\star)^{1/3}$, where M_p and M_\star denote the protoplanet and star mass, respectively and a the planet's orbital radius). The planetesimal accretion rate $dm_s/dt \propto \Sigma_s \approx 10^{-5} M_\oplus/\text{yr}$, where Σ_s denotes the local surface density of solids at the orbital radius ($\Sigma_s \simeq 3(a/5 \text{ AU})^{-3/2} \text{ g cm}^{-2}$ for the minimum-mass solar nebula (MMSN^{||})).

Once the solid core has grown of the order of a Mars mass ($\sim 0.1 M_\oplus$), it starts capturing an envelope of nebular gas and the protoplanet's growth is governed by a quasistatic balance between radiative loss and accretion energy due dominantly to planetesimals (planetesimals are supposed to sink to the planet's central regions whereas the accreted gas remains near the surface), with a negligible contribution from the PdV contraction work. Both solid and gas accretion rates are relatively constant during this phase, with gas accretion exceeding the planetesimal one. Above a critical mass M_{crit} , a static envelope can no longer be supported. Gravitational contraction is now necessary to compensate the radiative loss, which increases in turn gas accretion, leading to a runaway process, and the core accretes a massive gas envelope, becoming a newborn giant planet. For an envelope dust-dominated opacity ($\kappa \sim 0.1\text{--}1 \text{ cm}^2/\text{g}$), $M_{crit} \sim 10 M_\oplus$, although with large possible variations due to the sensitive dependence of M_{crit} upon the envelope composition (mean molecular weight, opacity), the planetesimal accretion rate and the distance of the planet to the star [8, 27]. At this stage, the mass of accreted gas is comparable to the mass of accreted planetesimals and the atmosphere has grown massive enough that its radiative loss can no longer be balanced by planetesimal accretion. The massive (dominantly H/He) envelope can no longer maintain quasi-static equilibrium and it falls in free fall onto the central core. The nascent planet's radius is essentially fixed by this accretion shock condition. This process, and thus the expected radius and luminosity of young planets, however, remains ill determined, given the lack of a proper treatment of the radiative shock (see discussion in §6.2, [28, 29]).

The main problem faced by the conventional core-accretion model is that core growth takes longer than typical protoplanetary disk lifetimes, \lesssim a few Myr [30]. Giant planet cores can be obtained within the appropriate timescale either by increasing

[§] defined as solid objects present in protoplanetary disks.

^{||} The minimum-mass solar nebula is defined as the protoplanetary disk of solar composition that contains the minimum amount of solids necessary to build the planets of our Solar System ([25, 26]).

severely the disk density compared to the MMSN or by reducing drastically the accreting envelope opacity, allowing rapid core contraction. A reduced opacity implies dust grains significantly larger than in the ISM, and thus efficient settling in the warmer parts of the disk, where they are destroyed [31, 32]. Spiral density waves generated in the gas by the core, however, cause this latter to migrate inward, the so-called type-I migration, with a characteristic timescale $t_I = a/|\dot{a}| \sim \Omega^{-1}(\frac{M_*}{M_p})(\frac{M_*}{\Sigma_{gas}a^2})(\frac{H}{r})^2 \approx (\frac{M_*}{M_p})(\frac{r}{1\text{ AU}})$ yr, for values appropriate to the MMSN, where Ω denotes the protoplanet's Keplerian angular velocity and H the disk scale height [33, 34, 35]. This timescale is much shorter than the time required to build up a 10 M_{\oplus} core in standard core accretion models. These calculations, however, assume that the disk is laminar (linear planet-disk perturbations). Simulations including the effect of (MHD) turbulence in the disk show that the mean torque does not converge towards the value obtained in a laminar disk (at least for the duration of the simulations) and that the usual type I migration is disrupted by turbulence [36, 37]. Analysis of these stochastic torques suggests that a planet can overcome type-I migration for several orbital periods, $P = 2\pi/\Omega$. Above a critical mass, of the order of 30 M_{\oplus} at 5 AU (although with large uncertainties) for typical protoplanetary disk conditions, the planet's gravitational tidal torque exceeds the viscous torque, eventually stopping the motion of the protoplanet. Deposition of angular momentum in the planet's vicinity, due to shock and viscous dissipation, pushes material away from the planet, clearing an annular gap in the disk [38, 33]. The planet is now locked in the disk and undergoes type-II migration with a timescale given by the disk viscous timescale $t_{II} \simeq 5 \times 10^6 \Omega^{-1}(\frac{10^{-4}}{\alpha})(\frac{10^{-1}}{(H/r)})^2(\frac{r}{10\text{ AU}})^{3/2}$ yr, assuming a Shakura-Sunyaev type viscosity law, $\nu = \alpha c_s H$, where c_s is the isothermal sound speed averaged over the vertical structure [38, 33]. Note that this timescale is now independent of the protoplanet's mass. Gap clearing and disk dissipation will limit the accretion onto the central core once the nebula starts falling down around it - although further accretion is possible if the protoplanet has an eccentric orbit - and the planet's final mass is set up by these limits.

Taking into account migration processes in the core-accretion model has been found to speed up core growth by increasing the supply of planetesimals, avoiding the depletion of the feeding zone obtained in the in-situ formation models and solving the timescale problem of the standard core-accretion scenario [39, 40]. Planets, including our own solar system giants, now form on a timescale consistent with disk lifetimes, with the appropriate observational signatures [39]. These models, however, have to reduce the conventional type-I migration rate by a factor ≥ 10 . It is currently not clear whether turbulent-induced stochastic migration can yield such a decrease over significant ($\gtrsim 10^5$ yr) timescales and the real impact of stochastic migration remains an open issue. Interestingly, recent core-accretion simulations including the concurrent growth and migration of *multiple* embryos find a global *negative* impact on planet formation: while migration indeed extends the domain of accretion for an embryo, this latter must also compete with other earlier generation embryos which have depleted the inner regions of solid material, reducing the final number of giant-planet cores [41].

In summary, including migration in the conventional core-accretion model succeeds in forming giant planets within appropriate timescales down to the inner edge of the disk. These models, however, use disk surface densities or dust-to-gas ratios about 2-3 times larger than the MMSN (suggesting that giant planet cores are unlikely to form in a MMSN) and require adequate planetesimal sizes and/or viscosity parameters α in order for giant planet cores to grow rapidly before type-I or type-II migration moves them into the star. Unfortunately, these parameters, which involve complex processes such as grain growth/fragmentation or turbulent viscosity are very uncertain and can vary over orders of magnitude.

3.2. Gravitational instability

The alternative theory for giant planet formation is direct gravitational fragmentation and collapse of a protoplanetary disc, the so-called gravitational instability (GI) scenario [42, 43], originally suggested to circumvent the timescale problem of the original core-accretion scenario. Instability to axisymmetric (ring-like) perturbations in a disk occurs when the Toomre's stability criterion is violated, i.e. $Q = c_s \kappa_e / \pi G \Sigma \sim T^{1/2} \Omega / \Sigma \sim \frac{M_* H}{M_d r} < 1$ [44], where κ_e is the epicyclic frequency at some point in the disk (for Keplerian orbits, the orbital and epicyclic frequencies are nearly the same whenever the disk mass is small compared to the stellar mass), $\Sigma \approx M_d / r^2$ is the surface density, $H \sim c_s / \Omega$ is the disk vertical scale height and M_d is the disc mass contained within radius r . According to the Toomre criterion, the disk becomes unstable to its own gravity whenever the stabilizing influence of differential rotation or pressure is insufficient. Note that this criterion is governed by the local density and is thus a *local criterion* for fragmentation. In the nonlinear regime, *global* spiral waves develop for values of $Q \lesssim 1.3$ -1.7 with a growth time of a few orbital periods. This solution involves spiral modes that either saturate at low-amplitude via mode coupling, leading to rapid non-local angular momentum redistribution restoring gravitational stability with no disk fragmentation [45], or fragment the disk. Estimates of disk surface densities and the fact that typically $H/r \sim 0.1$ for protostellar discs indicate that disks with $M_d \lesssim 0.1 M_*$ are usually stable to GI. A disk, however, might become unstable during its evolution, for instance during its formation, if mass builds up faster than it is accreted by the star or, at later times, if the outer part of the disk, where stellar radiation is negligible, becomes sufficiently cool. For fragmentation to occur, however, the disk must cool quickly enough to avoid entering a self-regulated phase, i.e. the disk cooling time t_{cool} must satisfy the condition, often called Gammie criterion, for very-thin disks $t_{cool} < \xi \kappa_e^{-1}$, with $\xi \sim 3$ [46]. Indeed, the energy loss rate determines the effect of the instability : isothermal disks, in which energy is easily lost (and gained, in gas expansion) remain unstable and evolve violently whereas adiabatic disks tend to heat up and become more stable.

Energy transport and dissipation processes are thus key issues to determine whether or not planets can form from gravitational instabilities in a disk. A detailed analysis of these conditions [47] shows that planet formation by GIs can occur only in very massive

disks, $M_d \gtrsim 0.1 M_\odot$, at the very upper end of the observed distribution, and at large orbital distances, $a \gtrsim 100$ AU. Even when vigorous convection occurs, it does not lower t_{cool} enough to lead to fragmentation [48, 49]. Note also that stellar irradiation tends to hamper fragmentation.

An other key issue for planet formation by GI is the fate of the fragments. Even if the disk cools fast enough for fragmentation to occur, the fragments have to last long enough to contract into planet embryos before being disrupted by tidal stresses, collisions or shocks. Moreover, the typical mass scale associated with the fastest-growing density perturbations in a disc undergoing GI, for $H/r \sim 0.1$ and $M_\star = 1 M_\odot$, is of the order of a few Jupiter masses [47]. An important question is whether such a fragment can form a core since at such relatively high initial central temperatures, less than 1% of the gas can condense into grains and one has to invoke efficient sedimentation of silicate and iron grains to the center during the early contraction phase to be consistent with the enhanced heavy element abundances relative to solar values inferred for our giant planets (see §2.1 and Tables 1-2). Therefore, it is far from clear that the peculiar composition and structure of our jovian planets can be explained within the GI model. Fragmentation by GI thus remains controversial, with markedly different results from various groups, and requires that the disk detailed thermal energetics are properly taken into account (see e.g. [50, 51] for recent reviews).

3.3. Core-accretion versus gravitational instability

It is interesting to point out that disk instability predicts that even very young ($\lesssim 1$ Myr) stars should harbor gas giant planets, whereas the formation of such planets with the core accretion scenario requires a few Myr. Observational searches for the presence of genuine giant planets around ~ 1 Myr-old stars will thus provide crucial tests for the two formation scenarios¶. As mentioned above, determination of the heavy element abundances of extrasolar planets also provides a definitive test: compositional similarity of planets and their parent star would strongly favour gravitational collapse whereas significant heavy element enrichment of the planet with respect to the parent star composition would rule it out. The large heavy element enrichment inferred for several transiting planets (see §2.2) clearly supports the core accretion model. Last but not least, the efficiency of planet formation by GI should not depend on the disk metallicity, since gravitational collapse from the protoplanetary disk is a compositionally indiscriminating process, contrarily to the core-accretion scenario. The observed clear dependence of planet frequency with the host star metallicity (see §2.2) and the suggested trend that metal-depleted stars seem to harbor lower mass planets ($M \sin(i) \lesssim 1 M_{Jup}$), i.e the lack of massive planets around metal-poor stars and the fact that stars hosting Neptune-mass planets seem to have a flat metallicity distribution [1]

¶ For this test to be meaningful, it is crucial to identify the stellar companion as a genuine metal-enriched *planet*, not as a brown dwarf of similar mass. Indeed, GI-induced fragmentation can occur during the early (dynamical) stages of protostellar collapse and rapid disk accretion, but objects formed by fragmentation in these cases are companion stars or brown dwarfs, not planets.

clearly suggest that metallicity plays a crucial role in planet formation, in agreement with the core-accretion model. Furthermore, statistical analysis of *null detections* in direct imaging surveys place constraints on the occurrence of giant extrasolar planets around FGKM stars. Calculations based on probability distributions derived from observed mass and semi-major axis distributions of extrasolar planets [52], show that $4 M_{\text{Jup}}$ and larger planets are found around less than 20% of stars beyond about 60 to 180 AU, depending on the planet theoretical models, *i.e* beyond the equivalent of extrasolar Kuiper belts, at 95% confidence level [53, 54]. Even though these calculations must be taken with caution (they do not include the few detected large orbit planets) and need to be confirmed by more detailed statistical analysis, they suggest that extrasolar giant planets at large separations ($\gtrsim 60$ AU) are rare. This observational constraint, combined with the statistical conclusion that the less massive the star the lower the likelihood to host a giant planet ($> 0.8 M_{\text{Jup}}$) [55] and with the theoretical constraints mentioned in §3.2, strongly weakens the GI model and reinforces the core accretion one. This latter thus appears most likely as the dominant scenario for planet formation.

The recently detected $3-M_{\text{Jup}}$ object Fomalhaut-b at projected separations > 100 AU from the central star [56], and other similar discoveries, challenge planet formation theories. Although local formation by GI is not excluded [57], formation by core accretion at shorter orbital distances remains a possibility, the planets having migrated outwards under the action of either planet-planet scattering [58, 59] or resonant interactions with an other planet in a common gap [60]. GI-induced planet formation, however, remains a plausible explanation in some peculiar situations, like for instance for the planets recently discovered orbiting a double SdB-M dwarf system [61]. In that case, the circumbinary disk is likely to be massive enough to become unstable.

4. Interior structure properties

The impact of planetary internal compositions on their radius goes back to the pioneering works of Zapolsky & Salpeter [62], who considered various zero-temperature single element compositions, and to Stevenson [8] for H/He, ice and rock planet compositions. Modern calculations, although basically similar to these studies, present improvements upon these works as they include modern equation of state (EOS) calculations, notably for H/He, and accurate atmospheric boundary conditions, taking into account irradiation from the parent star when necessary (see §6.3).

4.1. Thermodynamic properties

The mechanical structure and internal heat profile of a planet are entirely determined by the EOS of its chemical constituents. Indeed, due to efficient convective transport, the internal temperature profile is quasi-adiabatic. In the pressure-temperature (P - T) domain characteristic of planet interiors, elements go from a molecular or atomic state in the low-density outermost regions to an ionized, metallic one in the dense

inner parts, covering the regime of *pressure*-dissociation and ionization. Interactions between molecules, atoms, ions and electrons are dominant and degeneracy effects for the electrons play a crucial role, making the derivation of an accurate EOS a challenging task. We examine below our present knowledge in this domain.

4.1.1. Equation of state for H/He. The most widely used EOS to describe the thermodynamics properties of the gaseous H/He envelope of giant planets is the Saumon-Chabrier-VanHorn EOS (SCVH) [63]. This semi-analytical EOS recovers numerical simulations and experimental results in the high-density and low-density regimes, respectively, while, in its simplest form, interpolating over the pressure ionization regime. Thanks to the growth of computational performances, the properties of dense hydrogen can now be calculated from first-principle or nearly first-principle quantum mechanical calculations. The last generation of these ab-initio calculations seem to converge towards an agreement and to predict a substantially less compressible EOS for hydrogen, i.e. predict a lower density for a given pressure, than SCVH in the pressure-ionization domain, $P \sim 0.5\text{-}4$ Mbar (see [64] for a recent review of these EOS models). This bears significant impact on the internal structure of giant planets, in particular the size of the central core. A less compressible planet will tolerate less heavy material for a given radius or, conversely, will have a larger radius for the same internal composition [11].

Interestingly enough, high-pressure experiments on fluid deuterium⁺ or helium are now able to reach pressures and temperatures typical of the giant planet interiors ($P \gtrsim 1$ Mbar, $T \gtrsim 10^4$ K), probing the EOS in its most uncertain pressure-range. These experiments are dynamical, i.e. based on shock-driven compression. For a given initial state of the sample, mass, energy and momentum conservation across the shock, as given by the Rankine-Hugoniot relations, force the family of shocked states, which correspond to different shock velocities, to follow a Hugoniot curve in the (P, ρ, T) phase diagram. Dissociation or ionization processes absorb the corresponding amounts of energy and thus yield high degrees of compression with a modest temperature increase, whereas in the absence of such processes the energy of the shock is expended mostly in the kinetic degrees of freedom with a corresponding increase of temperature, following a different Hugoniot for the same initial state. Figure 3 portrays the phase diagram of hydrogen, with the pressure range presently probed by high-pressure dynamical experiments on H and He, together with Jupiter's internal adiabat. Various experimental techniques, however, give different results, with a $\sim 30\text{-}50\%$ difference in $P(\rho)$ in the maximum compression region for deuterium, $\sim 0.5\text{-}1.5$ Mbar, although the most recent experiments seem to converge towards the "stiff" (least compressible) Hugoniot result [65, 66], in agreement with the aforementioned quantum mechanical simulations (see [64] for various theory-experiment comparisons). This issue must be settled before hydrogen pressure ionization can be considered as correctly understood.

⁺ Because of the higher density of deuterium compared with hydrogen, higher shock pressures can be achieved experimentally for a given impactor speed.

For the less explored case of liquid helium, recent high-pressure experiments have been achieved up to 2 Mbar for various Hugoniot initial conditions, allowing to test the EOS over a relatively broad range. These experiments show a larger compressibility than for hydrogen, due to electronic excitations [67] and are in good agreement with the SCVH EOS while ab-initio calculations [68] underestimate the compressibility. Clearly more of these experiments, exploring the so-called "warm dense matter" domain, are needed to fully assess the validity of the various EOS models, with a crucial impact on our knowledge of the structure of Jovian planets [11, 13, 12] (see §2.1).

The combined interactions of H and He in the *mixture* increase drastically the degree of complexity in the characterization of the plasma. Not only the interactions between the two fluids will affect the regime of pressure ionization compared with the pure components, but partial immiscibility between the two species has been suggested to explain Saturn's excess luminosity for the age of the Solar System [69, 70, 71], and may occur inside some exoplanets. A phase separation in the interior of a planet strongly affects its cooling history. Indeed, if H/He phase separation (or immiscibility of other species with H) occurs in a planet's interior, He-rich droplets will form in a surrounding H-rich fluid and will sink to the planet's center under the action of the gravity field. This extra source of gravitational energy converted into heat slows down the planet's cooling, or alternatively yields a larger luminosity for a given age. The strongest suggestion for a phase separation in Jupiter or Saturn interiors comes from the observed depletion of helium in their atmosphere, with a mass fraction $Y = 0.238 \pm 0.05$ measured by the Galileo probe for Jupiter, and a more uncertain determination, $Y = 0.18-0.25$ inferred from Voyager observations for Saturn, to be compared with the protosolar nebula value, $Y = 0.275$ [6]. Unfortunately, given the aforementioned difficulty in modelling the properties of H or He alone, and the necessity to simulate a large enough number of particles for the minor species (He in the present case) to obtain statistically converged results, no reliable calculation of the H/He phase diagram can be claimed so far. As mentioned above, pressure-ionization of pure hydrogen and helium must first be fully mastered before the reliability of the calculations exploring the behaviour of the mixture can be unambiguously assessed*.

Resolving these important issues concerning the H and He EOS must await (i) unambiguous experimental confirmation of the H and He EOS at high pressure, (ii) unambiguous confirmation of the reliability of the theoretical calculations, in particular in the pressure ionization regime, (iii) guidance from experiments to predict the behaviour of the H/He mixture under planetary interior conditions. Progress both on the experimental and theoretical side will hopefully enable us to fulfill these criteria within the coming years (see section 9).

* Note that the recent claim [72] that H/He phase separation can not take place in Jupiter's interior, because metallisation of He should occur at lower pressure than previously expected, is not correct. Although such a facilitated metallization (by itself a model-dependent result) could exclude the suggested H^+ -He immiscibility [73], it does not preclude at all the H^+ - He^{++} one.

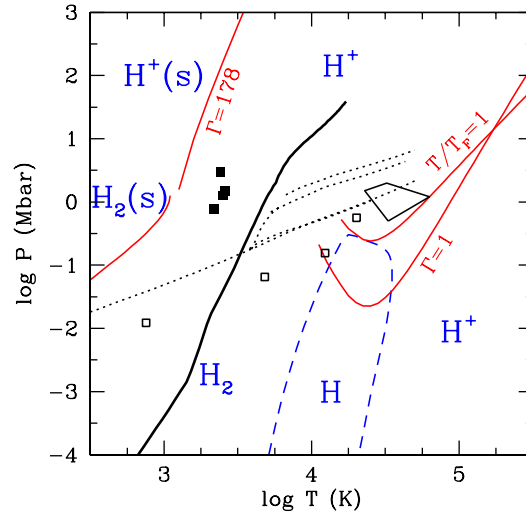


Figure 3 Phase diagram of hydrogen. Solid lines indicate dimensionless physical parameters ($\Gamma = (Ze)^2/kTa_i$, where a_i is the mean interionic distance, is the so-called plasma parameter, with $\Gamma = 1$ delineating weakly correlated from strongly correlated plasma regions and $\Gamma = 178$ indicating the solid-liquid melting line for a bcc-lattice, and $\theta = kT/kT_F$, where kT_F is the electron fluid Fermi energy, is the so-called degeneracy parameter). The dashed curves indicate the 50% dissociation and ionization boundaries. The dotted lines indicate regions probed by single, double and triple shock experiments on *deuterium* while filled squares show recent near entropic compression data [84]. The open squares indicate single and double shock data for *helium* [85] while the small polygon indicates the locus of recent shock wave experiments from pre-compressed initial states [67]. The heavy solid line illustrates the isentrope of Jupiter. *Figure kindly provided by D. Saumon*

4.1.2. Equation of state for heavy elements. According to the composition of the protosolar nebula, the next most abundant constituents after hydrogen and helium in gaseous giant planets, but the most abundant ones in ice giants and Earth-like planets, consist of C, N and O, often referred to as "ices" under their molecule-bearing volatile forms (H_2O , the most abundant of these elements for solar C/O and N/O ratios, CH_4 , NH_3 , CO , N_2 and possibly CO_2). The remaining constituents consist of silicates (Mg, Si and O-rich material) and iron (as mixtures of more refractory elements under the form of metal, oxide, sulfide or substituting for Mg in the silicates). The behaviour of these different elements as a function of pressure, under the conditions typical of giant planet interiors is not or poorly known. At very high pressure, the categorizations of gas, ice and rock become meaningless and these elements should become a mixture of closed-shell ions. The most widely used EOS models for such elements are ANEOS [74] and SESAME [75], which describe the thermodynamic properties of water, "rocks" (olivine (fosterite Mg_2SiO_4) or dunite in ANEOS, a mixture of silicates and other heavy elements called "drysand" in SESAME) and iron. These EOS consist of interpolations between existing Hugoniot data at low to moderately high ($\lesssim 0.5$ Mbar) pressure and Thomas-Fermi or more sophisticated first-principle calculations at very high density ($P \gtrsim 100$ Mbar), where ionized species dominate. Interpolation, however, provides no insight about the correct structural and electronic properties of the element as a function of pressure, and thus no information about its compressibility, ionization stage (thus conductivity), or even its phase change, solid or liquid. All these properties can have a large impact on the internal structure and the evolution of the planets. A detailed comparison between these EOS, and the impact of the uncertainties on the radius determination for Neptune-like and Jupiter-like planets has been conducted in [19]. The largest difference between the various EOS models, reaching up to $\sim 40\text{-}60\%$ in $P(\rho)$ and $\sim 10\text{-}15\%$ on the entropy $S(P, T)$, occurs in the $T \sim 10^3\text{-}10^4$ K, $P \sim 10^{-2}\text{-}1$ Mbar interpolated region, the typical domain of Neptune-like planets [19]. For these objects, such an uncertainty on the heavy element EOS translates into a $\sim 10\%$ uncertainty in the radius after 1 Gyr, and to larger uncertainties at earlier ages (Fig. 3 of [19]).

For solids, the lattice structure energy dominates the thermal vibration (phonons) contribution and, once the planet becomes cool enough for the core to become solid, the thermal contribution of this latter to the cooling of the planet can be neglected. This is not true at higher temperature, i.e. during the earlier stages of the planet's evolution, when the heavy elements are predicted to be in a liquid state, according to their EOS. In that case, thermal effects can substantially modify the zero-temperature structure contribution and assuming a zero-T or low-T core, i.e. neglecting the core release of thermal energy $(dU/dt)_{\text{core}}$ and gravitational energy $(P \frac{dV}{dt})_{\text{core}}$ can drastically underestimate its true gravothermal contribution, affecting the general cooling of the planet. The thermal contribution of the heavy elements to the cooling of the planet must then properly be taken into account for a correct description of the planet's evolution [19].

4.2. Internal structure and composition

There is compelling evidence from our own solar system planets that they are substantially enriched in heavy elements (C,N,O), with a ~ 3 to ~ 6 times solar value for Jupiter and Saturn, respectively, and even larger contrasts for Uranus and Neptune (see §2.1), as expected from a formation by core-accretion. This should apply as well to the discovered exoplanets. Indeed, the small radii of some of the observed transiting planets can only be reproduced if these objects are substantially enriched in heavy material, with a total of several tens to hundreds of Earth masses. For all these objects, including our own Jovian planets, however, uncertainties remain on (i) the total amount of heavy material, (ii) the respective fractions of "rocks" (silicates) and "ices", and (iii) the distribution of this heavy material in the planet's interior. As mentioned above, the first uncertainty (i) stems primarily from the present uncertainties on the various EOSs and should decrease with further experimental and theoretical progress. Addressing the two other issues necessitate to differentiate gaseous from solid/liquid planets.

4.2.1. Earth-like to super-Earth planets ($\lesssim 10 M_{\oplus}$) As discussed in §3, planets below about $10 M_{\oplus}$, usually denominated as super-Earth down to Earth-like planets, are not massive enough to enter the unstable, run-away regime leading to rapid accretion of a large gaseous envelope onto the central core. Post-formation degassing or oxydization processes can only produce a tenuous gaseous atmosphere, with no significant consequences for the planet's contraction. Therefore, these objects consist essentially of solids or liquids rather than gases, making their structure determination from mass-radius observations less uncertain than for more massive planets (see below). The mass-radius relationship for these low-mass planets has been parametrized as $R = R_{ref}(M/M_{\oplus})^{\beta}$, with $R_{ref} = (1 + 0.56\alpha)R_{\oplus}$ and $\beta = 0.262(1 - 0.138\alpha)$, for the rocky or ocean super-Earth planets in the mass range $1-10 M_{\oplus}$ ([76]), where α denotes the water mass fraction, and $\beta = 0.3$ for planets between 10^{-2} to $1 M_{\oplus}$, with a weak dependence upon the iron to silicate ratio Fe/Si [77]. Note that incompressible (constant density) material corresponds to $\beta = 1/3$. These parametrizations appear to be rather robust, despite the uncertainties in the EOS and in the iron/silicate fraction [78, 79, 77]. This provides a sound diagnostic for transiting Earth-like planet detections and the possible identification of the so-called "ocean planets", planets composed dominantly of water [80, 81], as opposed to the terrestrial (Fe-rich) planets. As mentioned in 4.1.2, current uncertainties in the high-pressure behaviour of silicates, ices and iron alloys prevent more precise information such as the detailed internal composition or the size and the nature, solid or liquid, of the central core. Exploration of the iron phase diagram and melting curve, in particular, a subject of prime importance for the characterization of the Earth inner core, has become even more interesting since the discovery of exoplanets of a few Earth masses (see §1) and the expected wealth of transiting Earth-size planets with the Kepler mission ([82]). While dynamic (Hugoniot) experiments produce too large temperatures at the pressure of interest for the Earth,

they might become relevant for the super-Earth objects. This again points the need for high-pressure experiments for planetary materials in the appropriate $\gtrsim 10^3$ K, $>$ Mbar regime.

4.2.2. Neptune-like to super-Jupiter planets ($\gtrsim 10 M_{\oplus}$) For planets with a $\gtrsim 10\%$ by mass gaseous (H/He) envelope, this latter essentially governs the gravothermal evolution of the planet. For instance, a $10 M_{\oplus}$ planet retaining a modest 10% H/He envelope is 50% larger than its pure icy counterpart [83, 19]. Under such conditions, a variety of internal compositions, either water-rich or iron-rich can produce the same mass-radius signature [83, 19] and detailed information about the planet's internal structure, other than inferring its bulk properties, becomes elusive. One of the main uncertainties about the internal structure is that we do not know whether these heavy elements are predominantly concentrated into a central core or are distributed more or less homogeneously throughout the gaseous H/He envelope.

A summary of the main consequences of the uncertainties (i) in the EOS, (ii) in the chemical composition and (iii) in the distribution of the heavy elements for planets with masses $\gtrsim 10 M_{\oplus}$ can be found in [19]. In particular, [19] show that for a global metal enrichment $Z \gtrsim 15\%$, all heavy material being either gathered in a core or distributed homogeneously throughout the envelope yields a $\gtrsim 10\%$ difference in radius after 1 Gyr for Neptune-mass planets and a $\gtrsim 4\%$ difference for Jovian-mass planets.

4.3. Energy transport properties

4.3.1. Giant planets The large radiative opacity of planetary material yields completely inefficient heat transport by photons, except in the most outer layers close to the planet photosphere (see §5). Transport by conduction, resulting from collisions during random motion of particles, may in some cases be relevant. In the central part of H/He dominated planets, thermal conductivity is dominated by electronic transport with conductivity $\kappa_T \sim 10^{-1} \text{ cm}^2 \text{ s}^{-1}$ ([69]). If no electrons are available, as in the outer envelope, conductive transport is dominated by the less efficient molecular motions with thermal conductivity $\kappa_T \sim 10^{-2} \text{ cm}^2 \text{ s}^{-1}$ ([69]). Conduction by electrons (or eventually phonons) may also dominate in central cores composed of heavy material (see [19]). But the dominant energy transport mechanism in giant planet interiors is convection. Large scale convection is extremely efficient in transporting heat ([86, 87]) and the temperature profile is close to adiabatic. Superadiabaticity is extremely small, with $\nabla_T - \nabla_{\text{ad}} \lesssim 10^{-8}$ in most of the interior \ddagger . For H/He dominated planets, convective velocities derived from the mixing length formalism vary between $\sim 10 \text{ cm s}^{-1}$, in the central regions, and a few 100 cm s^{-1} in the outer layers.

As initially stressed by [87], it is a conventional assumption in giant planet modelling to postulate that their interiors are fully convective and thus homogeneously mixed. This assumption has never been proven to be valid and has been questioned in the

\ddagger $\nabla_T = d \ln T / d \ln P$ is the local temperature gradient and $\nabla_{\text{ad}} = (d \ln T / d \ln P)_S$ the adiabatic gradient.

case of our own giant planets by [87]. As mentioned in §2.1, more recent models for Uranus have also suggested the possible existence of non-homogeneous regions where convection is not efficient. If compositional gradients exist, convection can break into convective layers separated by thin diffusive layers, the so-called double-diffusive or layered convection, or, if layers do not persist, overstable modes of convection can lead to the growth of small-scale fluid oscillations, the so-called oscillatory convection, becoming more alike an enhanced diffusion process than a large scale convective process [9, 70]. Layered convection is known to occur in laboratory experiments and in some regions of the Earth’s oceans or great lakes. In these conditions, the heat flux transport is significantly reduced because of the presence of multiple diffusive layers. If this process is present under conditions characteristic of giant planet interiors, heat transport in the diffusive layers is due to conduction with above-mentioned thermal conductivities ([88]). Because diffusion limits heat transport, the internal heat flow of the planet is significantly reduced compared with that of a fully convective object. This may bear important consequences on the planet structure and evolution, as discussed in §8.1, slowing down its global cooling and contraction ([87, 88]).

4.3.2. Terrestrial exoplanets Many efforts are devoted to the modelling of massive terrestrial planets, or super-Earths, essentially composed of heavy material, with a negligible amount of gas. Simplified models have been developed in order to investigate a wide range of compositions and masses ([79, 78]). These models involve simple internal structures and compositions (see §4.2.1). They use zero- or uniform, low temperature equations of state for the heavy material and thus do not consider the planet’s thermal structure. Such simplified models are advocated on the basis that, so far, only exoplanet bulk compositions can be inferred from mass and radius measurements, so that detailed planet interior models are not necessary [79]. In the future, however, internal structure models reaching a degree of sophistication comparable to our own Earth’s description might become required for terrestrial exoplanets. In this perspective, detailed models of massive Earth or super-Earth analogs have been developed ([77, 89, 90]). They rely on our knowledge of the Earth’s internal structure, appropriately rescaled to super-Earth masses. They involve layered internal structures with different compositions and phase changes, including an iron-rich core, lower and upper mantles composed of silicates and an outer water layer (icy and/or liquid), as well as the related temperature profiles. The effect of large amounts of water, characterising the so-called ”ocean-planets”, on the mass-radius relationships has also been investigated by [81]. The thermal profile is constructed according to the Earth thermal structure, which is determined by convective transport in each layer and is characterised by important variations at the interfaces. According to [89], the thermal structure has little effect on the radius of an Earth-like planet but imposes conditions on the compositional phases, particularly for water at the surface. This is of prime importance for the characterisation of ocean planets, in order to know whether or not they can have a liquid water surface [81, 76]. Typical terrestrial geological processes such as plate tectonics are now introduced in some exo-

Earth models, with the claim that this mode of convective transport mechanism might be important for massive terrestrial planets ([91]).

5. Atmospheric properties

The wide variety of planets both in and out of our solar system provide excellent laboratories for understanding how atmospheres evolve with time and react to their environments. Atmospheres by themselves hold a nearly endless supply of complex and interesting physical problems, but are also the primary link between observations and theory. The majority of observational techniques for studying planets involve capturing photons that have emerged from the atmosphere, placing extreme importance on our ability to successfully model atmospheric behavior. The grouping and location of substellar mass objects (brown dwarfs and giant planets) on color-color and color-magnitude diagrams is largely due to the sculpting of the emergent spectrum by atmospheric opacity sources. Also, as already mentioned above, the atmosphere regulates the release of energy from the interior and establishes the upper boundary condition for interior models. In the following sections, we discuss several of the important aspects of atmosphere modelling.

5.1. Chemistry, Clouds, and Opacities

Chemistry is at the heart of most atmospheric phenomena and establishes the distribution of the elements among various compounds. Among these compounds are the primary opacity sources which in turn play key roles in the radiative transfer. Planetary atmospheres are commonly assumed to be ideal gasses in chemical equilibrium. These assumptions greatly simplify the determination of mole-fractions (or partial pressures) of most compounds that, under these assumptions, depend only on temperature and pressure.

In principle, chemical equilibrium models are extremely simple and require the solution of a set of coupled nonlinear equations (for mass and charge conservation and including either equilibrium constants or chemical potentials). There are, however, practical considerations such as obtaining the necessary thermochemical data (specific heat, entropy, enthalpy, etc.) of enough compounds to ultimately end up with a realistic picture of the ensemble of chemical species. One must also correctly handle phase-transitions that produce liquid and solid species, which may or may not remain aloft in the atmosphere. Some of the first chemical equilibrium models applied to gas giant atmospheres were carried out for Jupiter and Saturn [92, 93]. Later, with the discovery of brown dwarfs, a variety of chemical equilibrium models were explored [94, 95].

The temperature structures for Jupiter, Saturn, a hot-Jupiter exoplanet (HD 189733) and a cool brown dwarf (of T spectral type) are shown in Fig. 4. In this figure pressure is used as a proxy for height, with pressure increasing toward the center of the object. For the two solar system planets the temperature structures have been

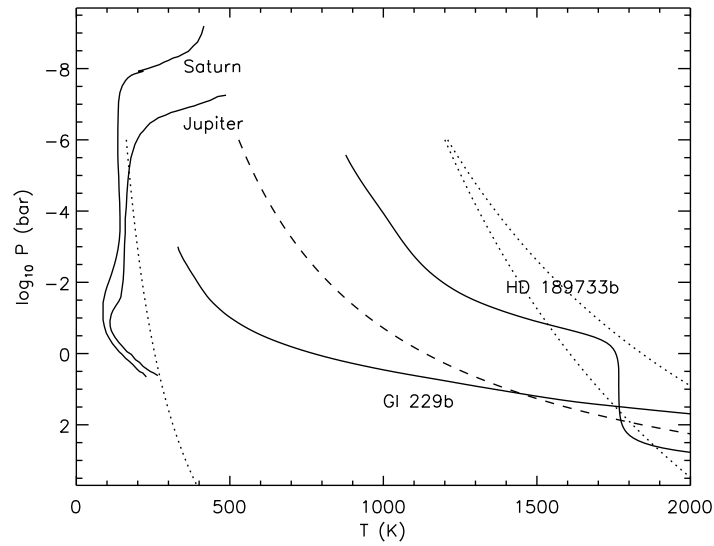


Figure 4 Temperature versus pressure for the atmospheres of Saturn, Jupiter, the brown dwarf Gl 229B, and the hot-Jupiter HD189733b. The dotted lines are the condensation curves of $\text{H}_2\text{O}(\text{ice})$, MgSiO_3 and Fe (from left to right). Equal mole fractions of CO and CH_4 follow the dashed line, with CO favored at higher temperatures.

carefully measured, while the brown dwarf and hot-Jupiter structures are theoretical predictions (while accommodating most available observational constraints). Figure 5 compares the mole fractions (or equivalently the partial pressure divided by the total pressure) for several of the most important molecules in a gas having the same element abundances as the Sun. Molecular hydrogen and He are by far the dominant constituents of the gas since H and He are orders of magnitude more abundant in the Universe than any other element. The next three most abundant elements (C, N, and O) make up the other dominant gas-phase molecules, H_2O , CO, CH_4 , N_2 , and NH_3 . From Jupiter to a hot-Jupiter, the atmospheric temperature range is in the thousands of Kelvin spanning a regime where water ice can form (in the case of Jupiter) and where all the water is in the gas phase. This broad temperature range also leads to a role reversal for CO and CH_4 as the dominant carbon-bearing molecule. In Jupiter, equilibrium chemistry predicts essentially no CO and nearly all of the carbon bound in CH_4 , while the reverse is true for the hot-Jupiter. The brown dwarf has intermediate temperatures but is in the region where water and methane are substantially more abundant than CO. Ammonia begins to increase in concentration near the temperature found in the brown dwarf example, and becomes increasingly important in the very low temperature atmospheres of Jupiter and the other solar system giant planets.

At the low temperatures encountered in planetary atmospheres, phase transitions can occur resulting in formation of liquid and solid “condensates”. The formation of condensates substantially alters the overall gas phase mole fractions and, for example,

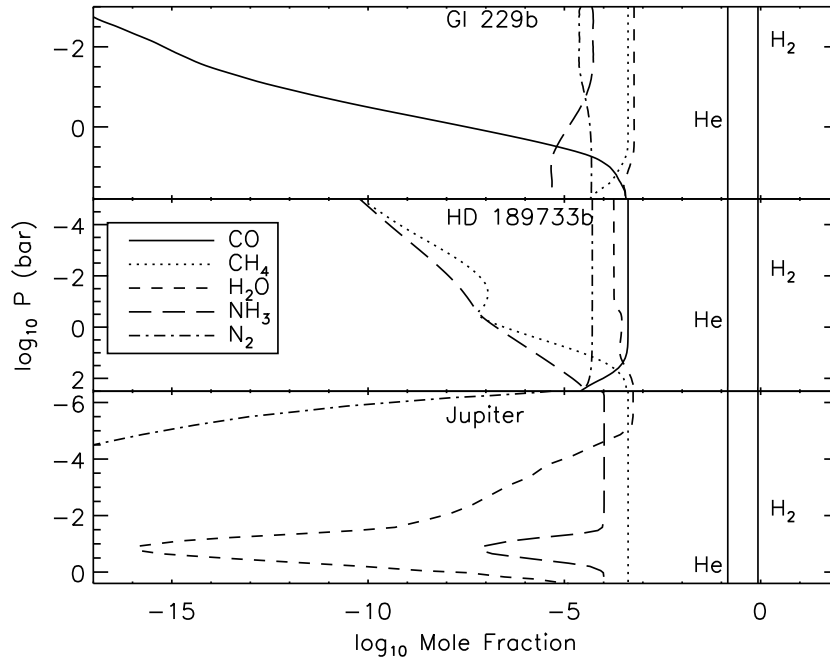


Figure 5 Equilibrium mole-fractions with pressure (a proxy for height) for the three temperature-pressure profiles shown in Fig. 4 and for the most abundant gas phase species. Drops in H_2O and NH_3 gas-phase mole-fractions are produced by the formation of water and ammonia ices. Departures from these equilibrium values have been observed in Gl 229B and Jupiter, see discussion in text.

explains the fairly dry conditions in Jupiter's atmosphere as water is expected to condense into ice with water clouds deep in the atmosphere (~ 5 bar). At higher temperatures other perhaps less familiar condensates are expected to form involving silicate grains and many other minerals (Fe , MgSiO_3 , Mg_2SiO_4 , Al_2O_3 and so on). In the presence of gravity and vertical/horizontal mixing, these condensates can potentially form stable clouds or potentially sink completely out of the atmosphere, taking with them elements that can no longer participate in the chemistry. Including clouds in atmosphere models is a significant ongoing challenge and a variety of approaches are being explored. Extreme limiting assumptions include either no clouds at all or clouds in pure chemical equilibrium, resulting in thick clouds extending high up in the atmosphere. More sophisticated models are used to explore the intermediate cases, many of which are phenomenological in design, with the expectation that the important cloud properties can be described by a manageable set of parameters with values ultimately determined empirically. The cloud-model parameters most frequently used control cloud thickness, particle size, and particle distribution. Alternatively, some models attempt to follow the micro-physics of nucleation and grain growth coupled to mixing within the gas. So far, no single model provides a comprehensive physical description of clouds. There is a long history of cloud modelling for the giant planets in our Solar system [96] and many of these have inspired cloud models used for exoplanet atmospheres [97]. Through the

study of brown dwarf atmospheres, a great deal has been learned about cloud formation across a wide variety of low-temperature environments that can be directly applied to exoplanet atmospheres. For a review of competing cloud models, mostly applied to brown dwarf atmospheres, see [98].

The importance of the chemistry and clouds are translated to the rest of the model atmosphere via the opacities, either directly or indirectly. Opacity sources are crudely divided up as either continuous (e.g., scattering, bound-free, or free-free), or line opacities (atomic and molecular transitions) and the relative importance of these is highly dependent on temperature and pressure as well as wavelength. The continuous opacity sources are generally well characterized in atmosphere models; however, for many grains, optical constants have either incomplete wavelength coverage or are not available at all. Perhaps the most problematic source of opacity over the years has been the molecular line opacity, where either the line data were simply not available or the ability to include all of the necessary lines was computationally prohibitive (requiring straight-means, K-coefficients, or the “Just Overlapping Line Approximation” (JOLA) to be used. For a description of these, see [99]). Modern computers are now quite capable of include millions of spectral lines, and model atmospheres can now include all the line data available to produce very realistic spectra. Some of the biggest improvements have been made in the completeness of line data for water vapor ([100, 101]). Other molecules like CH_4 still lack important line data at high temperatures (that are now very important given the temperature ranges encountered in planetary atmosphere studies).

5.2. Irradiation Effects

Of the more than 400 planets known, a third of these orbit their host star within 0.1 AU and, thus, receive a substantial amount of energy from the star. This large number of short period exoplanets is attributed to observational selection effects but, nonetheless, has greatly broadened our expectations for giant planets and in particular the conditions present in their atmospheres. In most of these cases, the amount of *extrinsic* energy received by the planet from the star greatly exceeds the energy leftover from the planet’s formation that slowly leaks from the interior. Consequently, unlike longer period planets and isolated brown dwarfs, the dominant energy source is a function of the orbital separation and the spectral type of the host star and is less dependent on an exoplanet’s mass and age (except for very young planets).

The incident flux can be defined by the following equation, where R_\star and T_\star are the host star radius and effective temperature, and $\alpha \in [1/4, 1]$ is a scaling factor used to crudely account for day-to-night energy redistribution.

$$F_{inc} = \alpha \left(\frac{R_\star}{r(t)} \right)^2 \sigma T_\star^4. \quad (1)$$

Since exoplanets are found with a wide range of eccentricities, the general (time-dependent) planet-star separation is given by,

$$r(t) = \frac{a(1 - e^2)}{1 + e \cos \theta(t)}, \quad (2)$$

where a is the semi-major axis, e is the eccentricity, and $\theta(t)$ is the angle swept out by the planet during an orbit.

The atmospheric temperature of isolated stars (and of widely separated planets and brown dwarfs) is often described by a single characteristic temperature, the so called effective temperature, T_{eff} , defined such that σT_{eff}^4 equals the total energy per unit area radiated from the surface. A similar characteristic temperature is useful for describing the temperature of irradiated planets, however, it is customarily called the equilibrium temperature (T_{eq}) to avoid confusion with the internal (T_{int}) effective temperature which is a measure of the energy contribution from the interior. Since energy is conserved, a planet in equilibrium must reradiate the energy it receives from the star along with the energy escaping the planet's interior. Thus the equilibrium effective temperature is given by,

$$\sigma T_{eq}^4 = \sigma T_{int}^4 + (1 - A)F_{inc}, \quad (3)$$

where A is the bond albedo.

As one would expect, the extrinsic flux heats the dayside of giant planet atmospheres to temperatures well above those found in our Solar System. The predicted temperature structure of HD189733b (Fig. 4) illustrates this point. The intrinsic flux of this planet is very close to that of Jupiter, while the predicted temperatures across the dayside atmosphere are entirely maintained by stellar heating. The discovery of the first hot-exoplanet, 51 Peg b, inspired many predictions for the properties of irradiated planetary atmospheres [106, 107, 108, 109, 110] with each of these early works employing simplifying assumptions ranging from ad hoc temperature structures, artificial upper/lower boundary conditions, and sparse chemistry and opacity descriptions. Despite simplifying assumptions, these early models successfully predicted many of the fundamental properties now revealed by observations and paved the way for more detailed models. More sophisticated 1-D models including state-of-the art chemical and radiative transfer simulations have been explored for a broad range of hot-exoplanet atmospheres, and have demonstrated the diversity and complexity one should expect in hot-Jupiter atmospheres, both chemically and spectroscopically [111, 112, 113, 114, 115, 116].

Early on, it was clear that traditional 1-D model atmospheres faced a geometric problem concerning the natural division of a hot-exoplanet into day and night sides. Many of the short-period planets should be synchronously rotating (see §7), ensuring that the planet is irradiated constantly on the same hemisphere. This of course was not a new problem as stellar and planetary atmosphere modelers have been dealing with this issue for decades earlier. In many ways, the situation is far more similar to

what is often encountered in irradiated stellar atmospheres since the expected day-night temperature differences for hot-exoplanets greatly exceeds what one finds in the Solar System (assuming hydrostatic and radiative-convective equilibrium). The frequently used approach is to model the two sides (day and night) separately and scale the incident flux by a geometric factor (α in the equations above) to account for the redistribution (or lack of) of absorbed stellar flux across either the day side or the entire atmosphere.

The value of this global redistribution factor has only recently been estimated using observations in a few cases and more sophisticated 3-D dynamical simulations are needed to predict wind speeds and horizontal heat transport. Early 3-D global circulation models [117] found that wind speeds could exceed 1 km s^{-1} and that day-night temperature differences of 500K were possible at photospheric depths (i.e. the spectrum forming region). These authors also stressed that dynamics has consequences for the chemistry, potentially leading to observable departures from equilibrium (see below). Different approaches have been used to model the circulation patterns in hot-exoplanets, including 2-D [118, 119, 120] and 3-D [121, 122, 123, 124] models, most of these motivated by varying successes within the Solar system planets. To accommodate the computational expense of following multi-D global circulations, these models make various levels of sacrifices when it comes to the radiative transfer in the atmosphere models. There still remains a substantial disconnect between the 1-D static atmosphere models with sophisticated radiative transfer and the multi-D global hydrodynamical models; however, efforts are underway to bring the two together [125]. While these circulations models differ in the details (some have large vortices like the spots on Jupiter, while others have single dominant westward jets), most agree that strongly irradiated planets will develop a small number of broad flows/jets [126]. This differs from the Solar System planets which have numerous narrow jets. See [127] for a recent detailed review of exoplanet circulation models.

5.2.1. Albedo Observational upper limits on the reflected starlight of hot-Jupiters yield a rather small value for the geometric albedo. None of the attempts to detect the reflected light from the ground during secondary eclipses has been successful so far. Space-based photometric observations of HD209458b at visible wavelengths are the most constraining upper limit so far, and give a value less than 0.17 at 99.5% confidence level [128], significantly smaller than Jupiter's value of 0.5. These observations suggest that most of the incident starlight of a hot-Jupiter, at least for HD209458b-like conditions, is absorbed, ruling out the presence of many reflective clouds in this type of object. Further observations on a large sample of transiting planets are necessary in order to obtain more stringent information about the albedos and the atmospheric properties of these objects.

5.3. Non-equilibrium Chemistry

Departures from equilibrium chemistry can occur for a variety of reasons, such as non-local phenomena (external radiation) and time-dependent mixing (vertical and/or horizontal). For example it is believed that enhanced tropospheric CO in Jupiter's atmosphere is due to rapid vertical mixing and very slow chemical reaction timescales to convert CO back to CH₄. Similar mixing-induced equilibrium departures are thought to occur in the atmosphere of brown dwarfs (e.g. Gl 229B), impacting both the CO/CH₄ ratios and the N₂/NH₃ ratios.

The (net) chemical reactions responsible for converting CO to CH₄ and N₂ to NH₃ are,



and



The individual times (τ_{chem}) for the two reactions above are very long, from left to right, at low temperatures and pressures (often greater than 10⁶ years) compared to vertical upwelling, which operates on year timescales or less. In both planetary and brown dwarf atmospheres the true mixing timescales (τ_{mix}) in the radiative layers are highly uncertain and often approximated as $\tau_{mix} \sim H^2/K_{zz}$, where H is the pressure scale height and K_{zz} is the eddy diffusion coefficient – a free parameter ranging from 10² to 10⁵ cm² s⁻¹ (see [129] for more details). When $\tau_{mix} \gg \tau_{chem}$, the chemistry is expected to be in equilibrium. All other reaction pathways involving important opacity sources occur very rapidly and, thus, are not expected to be perturbed from equilibrium by mixing. See [129, 130, 131] for applications of this procedure to brown dwarf atmospheres and [132] for CO in Jupiter's atmosphere.

As already mentioned above, global circulations can lead to horizontal/vertical mixing and cause departures from equilibrium chemistry. In many of the hot-Jupiters large mole fractions of CO can persist even in cool regions ($P \lesssim 1\text{bar}$) where chemical equilibrium predicts CH₄ as the dominant carbon bearing molecule in a manner very similar to that described above for brown dwarf atmospheres [122]. Looking back at Fig. 5, mixing is expected to elevate the CO mole fractions at low pressures ($P \lesssim 1\text{bar}$) by many orders of magnitude above the chemical equilibrium curves shown. NH₃ could also be an order of magnitude below the equilibrium value through much of the atmospheres shown. Photochemistry driven by external irradiation has been studied extensively in Solar System planets (see [133] for a review) but has only been studied in close-in giant exoplanets for a few specific cases [134]. Also, a new field develops with the study of photochemistry of Earth-like atmospheres, one of the motivation being the analysis of "false positive" signals of life due to photochemistry ([135, 136], see below).

5.4. Biosignatures

No Earth analogs have been yet detected, but their search is one of the major goal of ground- and space-based research programs of the coming decades. Our current understanding of planet formation suggests that terrestrial planet formation should be an efficient process. We thus expect these planets to be common, as illustrated by our Solar System which has three such planets (Earth, Mars and Venus). The search for signatures of life on exo-Earths is one of the main motivations for these programs and certainly one of the most exciting scientific inquiry of the beginning of the century. A huge activity is now devoted to astrobiology and we will only mention in this review the most basic biosignatures currently suggested. Biogeochemical activity on a planet could manifest itself through spectral features of the atmosphere. Current search strategies, as derived for DARWIN/TPF ([137]), are thus based on the spectroscopic detection of compounds that could not be present on a planet in the absence of life. The search for biomarkers is based on the assumption that extraterrestrial life shares fundamental characteristics with life on Earth. This later is based on carbon chemistry and requires liquid water as solvent. Other paths for life, based on a different chemistry, could perhaps exist but the signatures of the resulting life-forms are so far unknown. The need for liquid water leads to the concept of Habitable Zone defined as the region around a star where the surface temperature of Earth-like planets allows the presence of liquid water (see Fig. 6). This zone depends on the stellar luminosity and thus evolves in time with the star. Its definition also depends on complex processes on the planet, such as the concentration of greenhouse gases or geological activity (see [138, 136] and references therein). Any biomarker should include the signature of H_2O , which is a requisite for "earth-like" life. The presence of H_2O , O_2 (or O_3) and CH_4 , NH_3 or CO_2 would imply some biological activity, so that these elements are considered as favourite biomakers ([138, 137]). However, as pointed by [135], the unique detection of one of these compounds may be ambiguous. Indeed, O_2 , and hence O_3 , can be produced by photochemistry. The combined detection of O_2 with H_2O and CO_2 , which are important for habitability, would however provide a robust signature of biological photosynthesis ([135, 138, 137]). Similarly, the presence of CH_4 or NH_3 together with O_2 or O_3 would be good biomarkers (see [137] and reference therein), as demonstrated by the observations of the Galileo probe, as it passed near the Earth and detected simultaneously O_2 and CH_4 ([139]). Note that methane and ammonia are not expected to be abiotically produced on habitable, Earth-size planets, in contrast to a common production in cold hydrogen-rich atmospheres of giant planets (see §5.1 and Fig. 7). The analysis of biological spectral signatures on an exoplanet is thus optimised if its physical properties, such as its mass and radius, can be also determined.

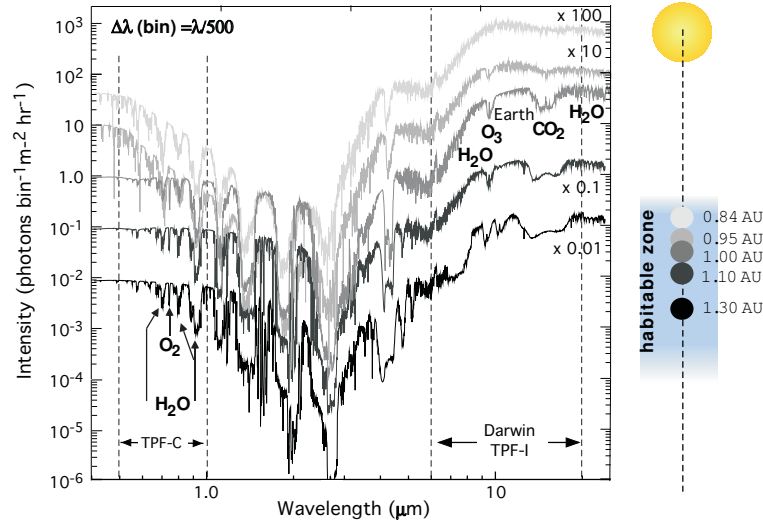


Figure 6 Spectra of an Earth-like planet at different orbital distances from a Sun-like star. The figure illustrates the evolution of the spectral signature of H_2O , O_3 and CO_2 as a function of the planet's location in the habitable zone ([136]). The fluxes correspond to a system located at 10 pc. Note that, for clarity, the intensity of each spectrum at different orbital distances is multiplied by a factor given on the right hand side of the figure. *Figure kindly provided by F. Selsis.*

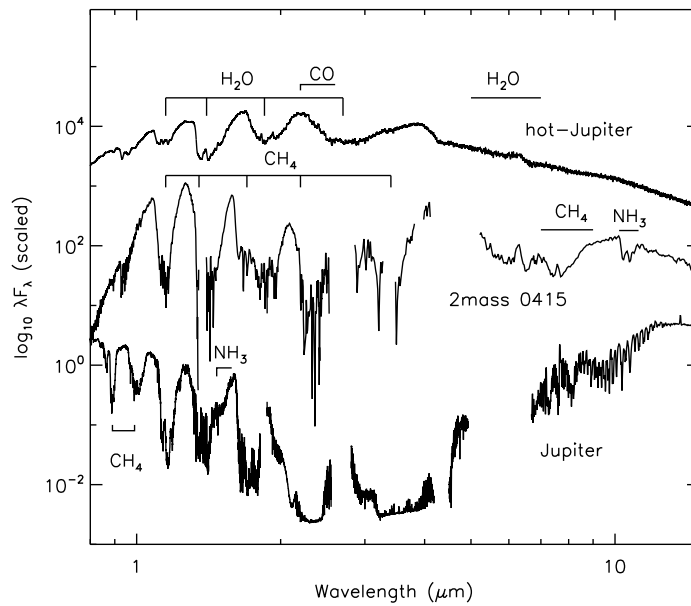


Figure 7 Observed spectra for Jupiter (Rayner, Cushing & Vacca (in prep.) and [102]) and the brown dwarf 2M0415 [103] are compared to a model spectrum of hot-Jupiter HD189733b [104]. Figure adapted from [103, 105].

6. Evolutionary properties

6.1. Basics of evolutionary models

Planetary evolution is described by the standard conservation equations, written in a spherically symmetric configuration and widely used in stellar evolution calculations ([5]). The complete evolutionary problem requires the coupling between interior (see §4) and atmospheric (see §5) structures. The rate at which internal heat escapes depends on the surface properties, and thus on the outer boundary conditions connecting interior and atmospheric structures. Modern models for planets incorporate realistic atmospheric boundary conditions using frequency dependent atmosphere codes as described in §5. This is required for a correct description of the thermal profile and effective temperature of objects having cold molecular atmospheres ([3, 140]). The inner and outer temperature-profiles are connected at large optical depths, where either the atmosphere becomes fully convective or radiative transport only involves Rosseland mean opacity, which is a weighted mean over all frequencies of the inverse monochromatic opacity κ_ν using the temperature derivative of the Planck distribution as weighting function (see [141]). The connection is done either at fixed pressure, usually at a few bars ([142, 5, 143]) or at fixed optical depth, usually at $\tau_{\text{Rosseland}} = 100$ ([3]). The numerical radius, corresponding to the outer boundary condition, provides to an excellent approximation the planet's photospheric radius, where the bulk of the flux escapes ($\tau_{\text{Rosseland}} \sim 1$). This stems from the negligible atmospheric extension between the photosphere and the depth characteristic of the outer boundary conditions.

6.2. Initial conditions

Planet evolution is characterised by the release of gravitational and internal energy from an initial (unknown !) entropy state. The usual procedure, similar to the brown dwarf and stellar cases, assumes a high initial entropy state, i.e. a large initial radius and luminosity [144, 140, 145]. Since this implies a relatively small ($\lesssim Myr$) Kelvin-Helmholtz timescale, this yields a rapid early evolution so that the initial conditions are forgotten within a few Myr and do not influence the subsequent evolution [148]. The assumption of a hot initial state for planets has recently been questioned by [29]. Using initial conditions derived from the core-accretion model, they find lower initial entropy states than aforementioned. These authors thus suggest that young giant planets should be fainter and smaller than predicted by standard evolutionary models, and thus fainter and smaller than young brown dwarfs at the same age. Although based on the planet embryo's core-accretion history rather than on a totally arbitrary initial condition, this approach, however, still suffers from the lack of a proper treatment of the final accretion shock, which determines the nascent planet's initial energy content and radius (see §3.1). The results of [29] are a direct consequence of the assumption that the accreting gas loses most of its internal entropy through the shock. Such assumption is derived from the shock boundary conditions of [146], which were initially developed for the

study of accretion onto protostars. Multi-D radiative transfer and hydrodynamical simulations of the accretion process and the resulting shock could provide more rigorous post-shock initial conditions for young planet models. Although still very challenging, this level of complexity seems to be required in order to improve the field. Therefore, the determination of the planet initial conditions remains so far an unsolved issue, as discussed in [28, 147].

Such a high sensitivity of early planet evolution to initial conditions, as previously stressed for low mass stars and brown dwarfs [148], has major consequences on the identification of planetary mass objects in young clusters and on detection strategies of future projects such as SPHERE and Gemini Planet Imager. The work of [29] also raises the question whether the faintness of young planetary mass objects may be used as a criterion to distinguish a brown dwarf from a planet. The answer is non trivial but one must keep in mind that accretion through a disk (circumstellar or circumplanetary) is a common process of both star and planet formation. Moreover, the conclusion that young planets should be faint relies on a treatment of accretion which can also be applied to the formation of protostars and proto-brown dwarfs (see [147] and §3). Thus, for the same reasons, brown dwarfs may as well be fainter than predicted by current evolutionary models.

6.3. Cooling and contraction history

A planet contracts and cools down during its entire life on a characteristic thermal timescale $\tau_{\text{KH}} \sim \frac{GM^2}{RL}$. For a $1 M_{\text{Jup}}$ gaseous planet, $\tau_{\text{KH}} \sim 10^7$ yr at the beginning of its evolution, starting from a hot initial state with luminosity $L > 10^{28}$ erg s⁻¹, and $\tau_{\text{KH}} > 10^{10}$ yr after 1 Gyr, reaching luminosities $L \lesssim 10^{25}$ erg s⁻¹ (see [144, 145]). As mentioned in §2.2, a non-negligible fraction of exoplanets are at close distance from their parent star and their evolution is affected by irradiation effects. These effects are accounted for through the coupling of interior and *irradiated* atmosphere structures (see §5). The heating of the outer layers by the incident stellar flux yields an isothermal layer between the top of the convective zone and the region where the stellar flux is absorbed. The top of the convective zone is displaced toward larger depths, compared to the non-irradiated case. The main effect is to reduce the heat loss from the planet's interior, which can maintain higher entropy for longer time. Consequently, the gravitational contraction of an irradiated planet is slowed down compared to the non-irradiated case and the upshot is a larger radius at a given age. This effect is illustrated in Fig. 8 on the evolution of a $1 M_{\text{Jup}}$ planet.

For Saturn and Jupiter mass planets with orbital distances 0.02-0.045 AU, the typical effect of irradiation on the radius is about 10%-20% ([145, 142, 149, 78]). Since the total binding energy and the intrinsic luminosity of a planet decreases with its mass, the lighter the planet, the smaller the ratio of its intrinsic flux to a given incident stellar flux. Consequently, the evolution and radius of a Neptune-like or smaller planet will be significantly more altered by irradiation effects, compared to the non-irradiated

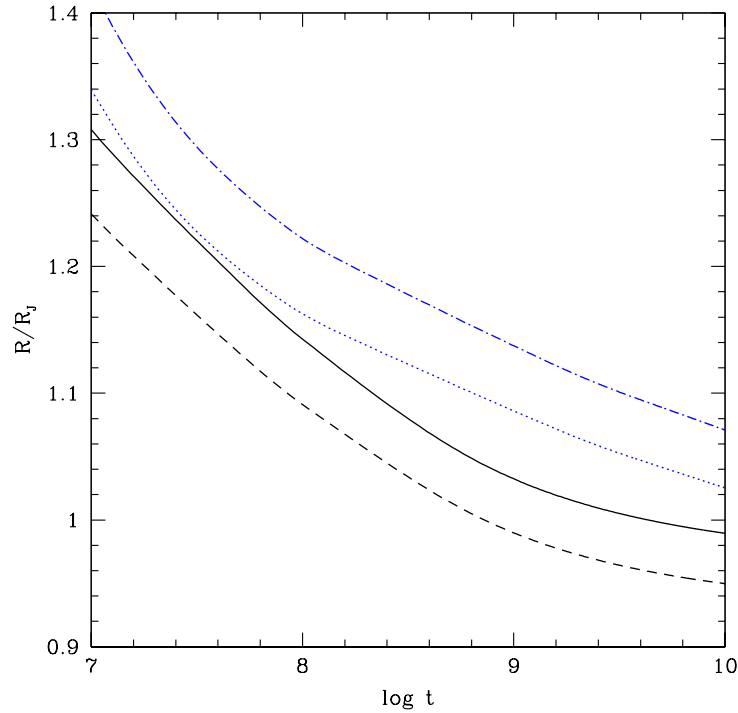


Figure 8 Effect of irradiation and of heavy element enrichment on the radius R as a function of time of a $1 M_{\text{Jup}}$ planet. Time is in year. Solid line: no core and no irradiation; dash-dotted line: irradiation from a Sun at 0.045 AU, no core; dashed line: no irradiation and a central core of water of 10% of the planet's mass ($M_{\text{core}} = 31.8 M_{\oplus}$); dotted line: irradiation and $M_{\text{core}} = 31.8 M_{\oplus}$. (Models from [19]).

counterpart, than for a more massive planet at a given orbital distance (see §6.4 and Fig. 9). Irradiation effects are thus quantitatively important and must be accounted for in the modern theory of exoplanet evolution.

Furthermore, a consistent comparison between theoretical radius and observed transit radius requires a subtlety due to the thickness of the planet atmosphere ([145, 142, 151]). The measured radius is a transit radius at a given wavelength, usually in the optical, which involves atmospheric layers above the photosphere. Atmospheric extension due to heating of the incident stellar flux can be significant, yielding a measured radius larger than the theoretical or photospheric radius. This effect can add a few % (up to 10%) to the measured radius ([145, 142]).

Inspection of transiting object mean densities suggests that some exoplanets, like the giant planets of our Solar System, are enriched in heavy material. Models devoted to the analysis of their properties must then account for such enrichment. Many efforts are now devoted to the construction of models, covering a wide range of masses, including (i) different amounts of heavy elements and (ii) different heavy material compositions ([150, 151, 78, 79, 19]). Exploration of effect (ii) is limited by available equations of

state valid under conditions encountered in planetary interiors (see §4.1.2). The most commonly considered materials are water, rock and iron. For sake of simplicity, and given the currently large uncertainties on EOSs, on the nature of the heavy elements and on their distribution inside the planet, current models often assume that heavy materials are all contained in a central core. A detailed analysis of the main uncertainties in current planetary models, due to EOS, composition and distribution of heavy material within the planet has been conducted in [19] (see §4.2.2). As shown in Fig. 8, the radius of a heavy material enriched planet is smaller, at a given time, compared to the H/He gaseous counterpart. Figure 8 also illustrates the competitive effects of irradiation, which increases R , and of the presence of heavy material, which diminishes R .

6.4. Mass-radius relationship

The mass-radius relationship of a planet at a given time of its evolution is entirely determined by the thermodynamic properties of its internal constituents and its ability to transport and evacuate its internal entropy content. Figure 9 portrays the behavior of the mass-radius relationship of Earth-like to Jupiter-like planets. The essential physics characteristic of the shape of the relation was described in the pioneer work by [62]. Two competitive effects yield the well-known flattening in the $M - R$ relationship around a few M_{Jup} . In the low mass regime, down to Earth masses, the dominant electrostatic contribution from the classical ions yields a relation $R \propto M^{+1/3}$, characteristic of incompressible matter. As mass and density increase, the effects of partially degenerate electrons start to dominate over Coulomb effects, yielding a reversal of the $M - R$ relation. Consequently, a maximum radius exists at a critical mass which depends on the planet composition. [62] found a critical mass of $2.6 M_{\text{Jup}}$, corresponding to a maximum radius of $\sim 1 R_{\text{Jup}}$, for a gaseous H/He planet under the assumption of zero-temperature plasma. More recent calculations, based on improved EOS as described in §4.1, yield a critical mass $\sim 3M_{\text{Jup}}$.

Figure 9 also illustrates the increasing effect of irradiation on the planetary radius as mass decreases for planets retaining a substantial atmosphere (see §6.3). The radius of a $20 M_{\oplus}$ planet with 50% H_2O is enhanced by $\sim 35\%$ if irradiated by a Sun at 0.045 AU ([19]). For terrestrial planets, the mass-radius relationship derived from detailed models assuming the same complex composition as for the Earth ([76], see §4.2.1) are shown by the long-dashed line in Fig. 9. As discussed in §4.3.2, these predictions are extremely close to the one derived from more simple models, assuming 100% rock ([78]). High accuracy (less than 5%) on radius measurement, and to a lesser extent on mass measurement, is thus required to infer the detailed composition of a super-Earth exoplanet ([77, 79, 76, 90]). As shown by [90], if the uncertainty on the radius of a super-Earth planet is less than 3%, the amount of water can be determined with an accuracy of less than 13%.

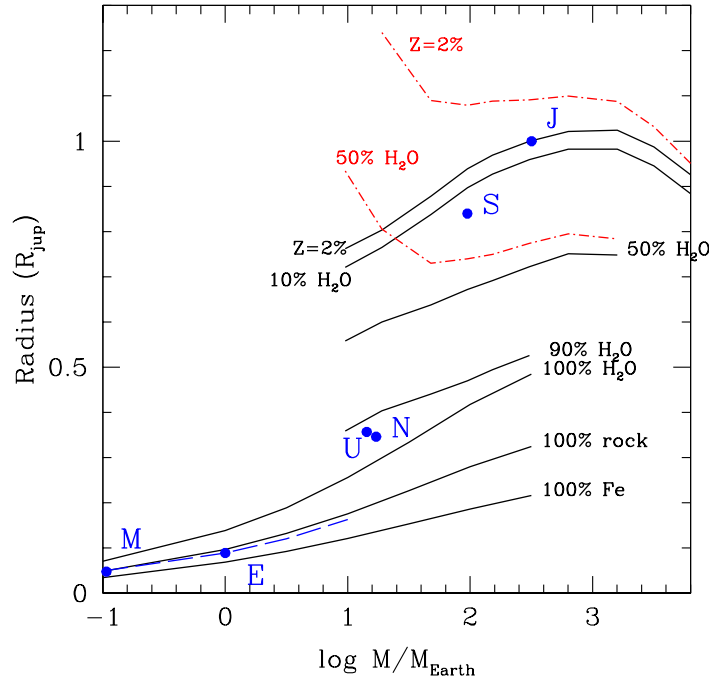


Figure 9 Planetary radii at 4.5 Gyr as a function of mass, from $0.1 M_{\oplus}$ to $20 M_{\text{Jup}}$. Models with solar metallicity ($Z = 2\%$) and with different amounts of heavy material (water, rock or iron) are shown (Models from [78, 19]). The "rock" composition here is olivine or dunitite, *i.e.* Mg_2SiO_4 . Solid lines are for non-irradiated models. Dash-dotted curves correspond to irradiated models at 0.045 AU from a Sun. The long-dashed curve, between $0.1 M_{\oplus}$ and $10 M_{\oplus}$, is the mass-radius relationship for terrestrial planets, with detailed structures and compositions characteristic of the Earth, after [76]. The positions of Mars, the Earth, Uranus, Neptune, Saturn and Jupiter are indicated by solid points. Note that pure heavy material planets (water, rock, iron) with masses $> 100 M_{\oplus}$ are unrealistic and are only shown for illustrative purposes.

7. Star-planet interaction. Tidal effects

7.1. Star-planet orbital parameters.

The geometry of an orbiting star-planet system of respective masses M_{\star} and M_p , illustrating the formation and dynamical evolution of the system, is encapsulated in three main parameters: the semi-major axis a , associated with the mean orbital motion, $n = 2\pi/P \simeq (GM_{\star}/a^3)^{1/2}$ where P is the orbital period and G the gravitational constant, the eccentricity e and the stellar obliquity ϵ , defined as the angle between the angular momentum vectors of the planetary orbit and the stellar rotation axis. This latter quantity, which determines the spin-orbit angle, is an interesting diagnostic for inferring the dominant interaction mechanisms at play in a protoplanetary disk: close

spin-orbit alignment (as is the case for our solar system) is expected from quiescent tidal interactions or migration processes of a planet within the disk whereas planet scattering events are prone to misalignments of planetary orbit angular momentum and stellar spins [162]. The inclination angle of the orbit relative to the sky plane is usually denoted i so that the line-of-sight projected value of a quantity retains a $\sin i$ indetermination. A transit observation implies that $i \sim 90^\circ$. Although the stellar obliquity is generally not measurable, Doppler shift observations on the parent star throughout a transit offer the possibility to determine the angle between the sky projections of the two angular momentum vectors, i.e. the projected spin-orbit angle λ , which gives a lower limit of the true three-dimensional spin-orbit angle^{††}. The angle λ is determined through the so-called Rossiter-McLaughlin (RM) spectroscopic effect [153, 154], originally applied to eclipsing binaries and recently extended to transiting planets [155, 156, 157] (see [157, 158] for recent reviews on RM observations). To date, the RM effect has been measured for 12 transiting systems. For nine of these systems, the determinations are consistent with a small ($\lesssim 3^\circ$) or even zero-value of λ , although with significant error bars in some cases, indicative of well-aligned spin and orbit, similar to the solar system, even though one should keep in mind that these observations provide minimum (projected) values of the true stellar obliquity, as mentioned above. Alignment of the stellar spin and the planetary orbital axis is a strong confirmation of planets forming in a spinning protoplanetary disk surrounding the central protostar. Spin-orbit *misalignment*, on the other hand, as found for the HD17156 [159], XO-3 [160] and WASP-14 [161] systems, can be produced by planet scattering or Kozai mechanism due to the presence of a third body (e.g. [162]). Interestingly, this spin-orbit alignment shows that the star's axis of rotation and the orbit angular momentum evolution are not significantly altered during the early episodes of angular momentum loss characterized by outflows and disk-star magnetic coupling. A less frequently addressed tidal parameter is the *planetary* obliquity, i.e. the angle between the planetary spin axis and the orbit normal. Although the planet's obliquity is expected to be rapidly damped by tidal dissipation, a persistent nonzero planet obliquity has been suggested as a result of the capture in a Cassini 2 spin-orbit resonance state as the nebula dissipates [163]. This scenario, however, has been excluded for hot-Jupiter-like planets [164, 165, 166]. Indeed, the resonant equilibrium is eventually destroyed by the strong tidal torque, leading the system to leave the Cassini 2 state and spiral towards the Cassini 1 state, with negligible obliquity [164, 166]. Therefore, close-in planets quickly evolve to a state with the planet's spin axis nearly normal to the orbit plane, i.e. a negligibly small planet obliquity. Note that the determination of stellar companion's obliquities would provide an interesting diagnostic to distinguish planets from brown dwarf companions, these latter being formed from

^{††}Since the orbit of transiting planets is nearly edge-on, the angle λ is related to the true stellar obliquity ϵ by $\cos \epsilon \simeq \cos \lambda \sin i_*$, where i_* is the inclination of the stellar rotation axis relative to the sky plane [152]. Note that for transiting systems, the projected spin-orbit alignment angle can be zero while the stellar obliquity is 90° if the angle i_* between the stellar rotation and the line-of-sight is also zero.

the same original gravoturbulent collapse of the parent cloud as the star, leading to arbitrary spin angle distributions.

7.2. Orbital evolution

For close planets, gravitational interactions between the planet and the star lead each of these bodies to raise tides on the other one, generating torques in the tidal bulges. Through exchange of angular momentum, these strong tidal interactions affect the system orbital (eccentricity, semi-major axis, obliquity) and rotational (stellar and planetary spin, ω_* , ω_p) properties. In the first calculations addressing tidal effects in the discovered extrasolar close-in star-planet systems [167, 168], coplanarization of the orbit and the stellar equator (i.e. stellar spin-orbit alignment), planet spin-orbit alignment, circularization of the orbit and synchronization of the stellar and planetary rotation with the orbital motion were implicitly assumed to represent the asymptotic *equilibrium states*, characteristic of the endpoint of tidal evolution, although the orbit might be *unstable*, leading eventually to star-planet merging [168]. Accordingly, the associated timescales were generally characterized by an exponential relaxation towards an equilibrium state [169, 170]. Furthermore, in the calculations of [167], only tides raised by the star on the planet were considered whereas tides raised by the planet on the star were ignored. A proper derivation of the evolution of all orbital and rotational parameters, however, requires to solve consistently the *complete* non-linear coupled tidal equations, taking *both the planetary and the stellar tides* into account. Note that tides raised in the star transfer angular momentum between the star's rotation and the planet's orbit, so that, in the presence of stellar tides, the planet's orbital angular momentum is *not* conserved during the tidal evolution, even if the planet's rotation is synchronized. Such consistent calculations lead to markedly different dynamical evolutions with significantly different rotational and orbital evolution timescales, and thus different eccentricity values from the ones obtained when neglecting stellar tides [171, 172, 173, 174, 175, 176].

As mentioned above, most of the early studies implicitly assumed the existence of a tidal (possibly unstable) minimum energy equilibrium state at given angular momentum for the orbiting planets, characterized by circular orbits (for the stable state), synchronous rotation and spin-orbit alignment. However, as demonstrated recently [174], none but one, namely Hat-P-2b, of the transiting planets discovered at this time (26 objects) has such an equilibrium state. Indeed, for all these systems, the total star-planet angular momentum, L_{tot} , is lower than the critical angular momentum defined as $L_c = 4 \left[\frac{G^2}{27} \frac{M_*^3 M_p^3}{M_* + M_p} (I_p + I_*) \right]^{1/4}$, where I_p and I_* denote the polar moments of inertia of the planet and the star, respectively. Consequently, no equilibrium state exists and all these planets will ultimately merge with the star [177, 178]. This result does *not depend on any particular tidal model* and bears major consequences on our analysis of the discovered transiting systems and, possibly, of the non-transiting ones too. First of all, it implies that the conventional tidal exponential damping estimates for the timescales

for semi-major axis evolution, synchronization of the spins and spin-orbit alignment are not valid, because the implied corresponding equilibrium states do not represent the endpoint of the tidal evolution. The full tidal calculations, taking into account the strong nonlinear coupling between e , a , ϵ , ω_* and ω_p show that the timescales characteristic of the semi-major axis and the stellar spin and obliquity evolution of these systems are now comparable, and equal to the lifetime of the system itself [174]. These quantities are found to evolve only moderately from their initial values, until they quickly go to zero or diverge during the final merging episode with the host star, the true endpoint of the tidal evolution for these systems. The only exception is the *pseudo*-synchronization of the *planet's* rotational velocity with the orbital motion, such as $\omega_p \sim n$, which occurs on a timescale comparable to the one estimated with the equilibrium tide theory, $\sim 10^5$ - 10^6 yr for hot-Jupiter typical parameters [167, 168, 174]:

$$\tau_{sync,p} = \frac{I_p}{\Gamma_p} |\omega_p - n| \approx 5.0 \left(\frac{\alpha}{0.25} \right) \left(\frac{Q'_p}{10^6} \right) \left(\frac{M_p}{M_{Jup}} \right) \left(\frac{R_p}{R_{Jup}} \right)^{-3} P_d^3 \text{ Myr}, \quad (6)$$

where $I_p = \alpha M_p R_p^2$ is the planet's moment of inertia ($\alpha \approx 0.25$ for Jupiter), $\Gamma_p = \frac{3}{2} \frac{GM_*^2 R_p^5}{Q_p' a^6}$ the amplitude of the torque exerted by the star on the planet, P_d the orbital period in days and $Q' = Q/k$, where Q_p (resp. Q_*) denotes the planet (resp. star) tidal quality factor. This latter is defined as the ratio of the maximum potential energy stored in the tidal distortion over the energy dissipated per tidal period, roughly equal to the inverse of the tidal phase lag associated to the (equilibrium) tidal oscillation in the body of interest (e.g. [179]), and k denotes the star or planet second order Love number, representative of the body's deformability (typical values of the Love number for Sun-like stars and for Jupiter are $k_\odot \approx 0.02$ and $k_{Jup} \approx 0.38$, respectively, although with large uncertainties). This quick planet pseudo-synchronisation stems from the fact that the planet's rotation angular momentum is much smaller than the orbital angular momentum. This state, however, corresponds to a *temporary state*, as the ultimate planet-star orbital collapse eventually causes the planet to spin up dramatically [174]. Once the planet is pseudo-synchronized, there is no further exchange of angular momentum between its rotation and its orbit; the only exchange occurs between the orbit, the eccentricity and the stellar rotation at constant total orbital angular momentum. These quantities are also modified by the tides raised by the star on the planet, in case of a non-zero eccentricity, and by the tides raised by the planet on the star even when/if the orbit is circularized.

This lack of tidal equilibrium state for the transiting systems bears other important consequences. First of all, it implies that, even for a circular orbit ($e = 0$), ongoing tidal dissipation keeps taking place in the *star*, leading, by conservation of angular momentum, to the planet's endless orbital decay and, inevitably, to a merging of the planet with the star. It also means that *stellar* spin synchronization with the orbit can never occur for these systems, since, once the planet is pseudo-synchronized, the tidal torque raised by the planet onto the star yields this latter to *spin up constantly* (indeed, for $n \gg \omega_*$, energy is transferred from the orbit to the spin [170]), the stellar spin

evolving within the same timescale as the orbital distance. Decrease of stellar rotation velocity with time due either to stellar winds or magnetic braking may counteract this tidal spin-up. Strong stellar wind episodes, however, mainly occur at the early stages of evolution and these effects are probably unimportant at the age of the observed systems. Magnetic braking is a more complex issue and is found to compensate or even dominate tidal spin-up if $Q'_\star \gtrsim 10^8$ for OGLE-TR-56b, the presently discovered extrasolar giant planet closest to its parent star [180].

As mentioned above, a proper determination of the various timescales, including the lifetime of the system, i.e. the time for the planet to merge with its host star (or more exactly to reach the Roche Lobe limit, $a \sim 2.5 (\rho_\star/\rho_p)^{1/3} R_\star$), requires to solve consistently the complete non linear coupled dynamical equations for a , e , ϵ , ω_p and ω_\star . No analytical solution exists. In the limit of small eccentricity ($e \ll 1$) and for $M_p \ll M_\star$, however, the timescale for orbital evolution is dominated by the tides in the *star* [172, 173, 174]†. In that case, providing that the orbital period is much shorter than the stellar rotation period ($\omega_\star \ll \omega_{orb} = 2\pi/P$), a fulfilled condition for most of the observed transits ($P_{rot,\star} \sim 3\text{-}70$ days whereas $P \lesssim 4$ days (see e.g. Table I of [174])), and that the stellar obliquity is small (also a generally fulfilled condition), the orbit evolution timescale, given by the inverse ratio of the torque exerted by the *planet* on the *star* over the orbital angular momentum, can be estimated as (e.g. [179, 170, 181, 172, 174])

$$\begin{aligned} \tau_a &\approx \left(\frac{\Gamma_\star}{M_p a^2 n}\right)^{-1} \approx 0.06 \left(\frac{Q'_\star}{10^6}\right) \left(\frac{M_\star}{M_p}\right) \left(\frac{a/0.02 \text{ AU}}{R_\star/R_\odot}\right)^5 P_d \text{ Myr} \\ &\approx 0.05 \left(\frac{Q'_\star}{10^6}\right) \left(\frac{M_\star}{M_p}\right) \left(\frac{\bar{\rho}_\star}{\bar{\rho}_\odot}\right)^{5/3} P_d^{13/3} \text{ Myr}, \end{aligned} \quad (7)$$

Note that this timescale quickly decreases with finite eccentricity since tidal effects increase drastically at the apside [174]. We stress again that eqn.(7) is only a rough estimate and that the proper determination of the orbit evolution requires a consistent solution of the full tidal equations. Moreover, the true calculation of the timescale depends to some extent on the used tidal model. Eqn.(7), however, provides some useful information. Since indeed, at very small eccentricity, τ_a only depends on (or more exactly is dominated by) tidal dissipation within the star, not within the planet, as seen from eqn.(7), a first consequence of this equation is that, for hot-Jupiter like systems:

$$\tau_a \lesssim \langle \tau_\star \rangle \sim 10 \text{ Gyr} \Rightarrow P \lesssim 3.4 \left(\frac{Q'_\star}{10^6}\right)^{-3/13} \text{ day}, \quad (8)$$

where $\langle \tau_\star \rangle$ is the average value of the lifetime of stars harboring planets (~ 10 Gyr for solar-type stars). Therefore, although all the planets for which $L_{tot} < L_c$ will merge with

† As mentioned in [174], even though only the outermost layers of solar-type stars are convective and dissipate efficiently, ultimately the convective and radiative zones will synchronize and dissipation will occur throughout the entire star. This will affect the timescale for tidal evolution, but this latter will qualitatively remain the same.

their host star, for the ones with orbital periods in the range $P \sim 1\text{-}10$ days, i.e. semi-major axis $a \sim 0.02\text{-}0.09$ AU, for a range of uncertainty $10^9 \geq Q'_\star \geq 10^4$, the merging will occur within the stellar lifetime. Note from eqn.(7) that this planet's lifetime decreases with increasing planet-star mass ratio, which has two major consequences. First of all, the more massive the planet, the faster the orbital decay and thus the shorter the system's lifetime, which may partly explain the lack of hot-Jupiters for $P \lesssim 3$ d [172, 183, 184]. Second of all, for a given orbital distance and comparable stellar masses, small transiting planets should be discovered around older systems, a trend which seems to be supported by observations [184, 185]. The often used assumption that tidal evolution is always dominated by tides raised by the star in the planet leads to the opposite behaviour. Conversely, as seen from eqn.(7), the determination of the age of the system from the age of the host star provides a constraint on the minimum value for Q_\star . As mentioned earlier, for observed transiting planets, the orbital period is shorter than the stellar rotation period, so that tidal dissipation in the central body (the star in the present context) *decreases* the orbital semi-major axis ($\dot{a} < 0$), by conservation of total angular momentum. This is similar for instance to the Mars-Phobos system but contrasts with the Earth-Moon one. In this latter case, the Moon revolution period is longer than the Earth rotation one so that tidal dissipation in the Earth leads to an increase of the Earth-Moon distance.

As for the orbital evolution timescale, there is no simple analytical solution for the orbit circularization timescale, τ_e , and one needs to solve the whole dynamical equation system. One can try, however, to estimate τ_e , as done above for τ_a . The rate of eccentricity decay reads

$$\frac{de/dt}{e} = -\left(\frac{1}{\tau_{e,p}} + \frac{1}{\tau_{e,\star}}\right), \quad (9)$$

where $\tau_{e,p}$ and $\tau_{e,\star}$ denote the characteristic timescales associated with the contributions stemming from the tides raised by the star in the planet and by the planet in the star, respectively. It can easily be shown (e.g. [182, 181]) that (for zero stellar obliquity)

$$\frac{\tau_{e,p}}{\tau_{e,\star}} = \left(\frac{M_p}{M_\star}\right)^2 \left(\frac{R_\star}{R_p}\right)^5 \left(\frac{Q'_p}{Q'_\star}\right). \quad (10)$$

It can be verified that, for the majority of the presently observed transit planets, $\frac{\tau_{e,p}}{\tau_{e,\star}} < 1$ (for $Q'_p \leq Q'_\star$), so that the eccentricity damping is dominated by tidal dissipation of the torque exerted by the *star* on the *planet*. In that case, the orbit circularization timescale can be estimated as:

$$\begin{aligned} \tau_e \approx \tau_{e,p} &\approx \left(\frac{\Gamma_p}{M_p a^2 n}\right)^{-1} \approx (5.3 \times 10^3) \left(\frac{Q'_p}{10^6}\right) \left(\frac{M_p}{M_\star}\right) \left(\frac{a/0.02 \text{ AU}}{R_p/R_{\text{Jup}}}\right)^5 P_d \text{ Myr} \\ &\approx 5 \left(\frac{Q'_p}{10^6}\right) \left(\frac{M_\star}{M_\odot}\right)^{2/3} \left(\frac{M_p}{M_{\text{Jup}}}\right) \left(\frac{R_p}{R_{\text{Jup}}}\right)^{-5} P_d^{13/3} \text{ Myr} \\ &\approx 0.04 \left(\frac{Q'_p}{10^6}\right) \left(\frac{M_\star}{M_p}\right)^{2/3} \left(\frac{\bar{\rho}_p}{\bar{\rho}_{\text{Jup}}}\right)^{5/3} P_d^{13/3} \text{ Myr}, \end{aligned} \quad (11)$$

As seen from eqns.(7) and (11) (and as expected from the fact that $\tau_{e,\star} \sim \tau_a$ for $e \ll 1$), the ratio of the orbital and circularization timescales in the limit of small eccentricity reads:

$$\frac{\tau_e}{\tau_a} \approx \left(\frac{M_p}{M_\star}\right)^2 \left(\frac{R_\star}{R_p}\right)^5 \left(\frac{Q'_p}{Q'_\star}\right), \quad (12)$$

i.e. $\tau_e/\tau_a \approx 0.1 (Q'_p/Q'_\star)$ for typical hot-Jupiter conditions. Therefore, for $Q'_p/Q'_\star \lesssim 10$, tidal damping may explain the circularization of initially eccentric orbits. Indeed, calculations solving the complete tidal dynamical equations show that tidal dissipation for short-period planets may have produced the present eccentricities from larger initial values similar to the longer period planet eccentricity distribution, providing an explanation for the smaller eccentricity ($e \lesssim 0.3$, $\langle e \rangle \sim 0.1$) of short-period ($a \lesssim 0.2$ AU) planets compared with more remote ones ($e \lesssim 0.9$, $\langle e \rangle \sim 0.3$), depending on the values of Q'_\star and Q'_p [173, 186, 175, 176]. For $Q'_p/Q'_\star \gtrsim 10$, however, the orbit does not have time to circularize within the lifetime of the system [187, 174]. In such cases, there is no need to invoke undetected companions to maintain the eccentricity. Note that a value $e=0$ is often assumed when constraining the orbital parameters by inferring a solution for (a, e) from the observed light curves in fitting the orbits of close-in planets. Eccentricity values for short-period planets should thus be taken with caution.

Integrating the *complete* coupled tidal evolution equations back in time from present eccentricity and orbital values[‡] may provide some clues about the initial eccentricity distribution of exoplanets, at the end of their formation process, and thus about the outcome of planet-disk interactions. Numerous Lindblad or corotation resonances take place between a disk and a planet, exerting torques which deposit or remove angular momentum from the resonance locations. This modifies the planet's eccentricity during the disk evolution [188]. The net effect of these disk-planet interactions on the eccentricity, however, remains uncertain, and it is not clear whether eccentricity is damped or excited, with possibly both solutions being valid depending on the disk and planet properties [189]. To first order, however, the eccentricity evolution due to disk torques is $\dot{e} \propto 1/\sqrt{a}$ [188], so it is expected that short period planets are more affected than the ones located further away. Planets could thus form with finite eccentricities, damped either by interactions with the disk [189] or by tidal interactions after the disk dissipation for the low eccentricity objects. On the other hand, large initial eccentricities can be produced by planet-planet scattering or gravitational perturbations by a stellar companion [190, 162].

As discussed in the next subsection, the orbital and rotational evolution timescales, however, can not be determined accurately, as they depend on the ill-determined tidal forcing and dissipation processes, as well as on the internal structure of the star and the planet (radiative envelope, presence of a dense core, etc...), which translates into values of Q uncertain by several orders of magnitude.

[‡] Present attempts to address this issue [173, 175, 176] do not consider the evolution of the stellar spin and use tidal equations truncated at the order e^2 , only valid for small eccentricity values, and thus yield quantitatively unreliable results.

7.3. Tidal energy dissipation

If the planet's orbit is circular, the tidal bulge is motionless in the planet's frame and there is no energy release. In the case of a maintained finite eccentricity or obliquity, however, the persisting tidal friction leads to energy dissipation in the planet, at the expense of the orbital and rotational energies. If the tidal heating induced in the planet by tidal dissipation dominates the planet's main sources of energy, gravothermal contraction and solar irradiation, about 10^{25} erg s $^{-1}$ for typical Gyr-old hot-Jupiters (*i.e.* $\sim 1 M_{\text{Jup}}$ at ~ 0.05 AU from a Sun-like star) and lasts over a timescale comparable to the planet's thermal timescale, this extra source of energy will slow down the planet's contraction, leading to a larger radius (and luminosity) at a given age than otherwise expected. At second order in eccentricity (*i.e.* in the limit $e \ll 1$), the tidal dissipation rate in a pseudo-synchronously rotating ($\omega_p \simeq n$) planet with zero obliquity is given, at given a and e , by (e.g. [191, 170, 192, 193]):

$$\begin{aligned} \frac{dE_{\text{tide}}}{dt} &= - \frac{21}{2} \frac{G^{3/2} M_{\star}^{5/2}}{Q'_p} \left(\frac{R_p^5}{a^{15/2}} \right) e^2 \\ &\approx - 5.2 \times 10^{27} \left(\frac{Q'_p}{10^6} \right)^{-1} \left(\frac{M_{\star}}{M_{\odot}} \right)^{5/2} \frac{(R_p/R_{\text{Jup}})^5}{(a/0.05 \text{ AU})^{15/2}} e^2 \text{ erg s}^{-1}, \quad (13) \end{aligned}$$

where the terms of orbital evolution only include the contributions due to the planetary tides, since we are presently interested in the energy dissipated in the planet. Tidal dissipation has been proposed to explain the abnormally large radii of some transiting planets [167]. As mentioned earlier, however, these estimates of orbital decay timescales were ignoring the stellar tides, leading to incorrect tidal dissipation rates. As a consequence, eccentricity and tidal dissipation were found to be negligible at the age of the presently observed transiting planets, and hypothesis like continuous gravitational interactions from undetected companions had to be invoked to maintain a finite eccentricity. Only recently have correct tidal evolution calculations been conducted to quantify this effect [171, 172, 173, 186, 174, 175, 176]. As mentioned earlier, the coupled tidal equations taking both star and planet tides into account yield significantly different timescales for the evolution of the orbital and rotational properties, with a non-monotonic evolution for the evolution of the eccentricity, semi-major axis and stellar spin, as well as for the tidal heating, and this latter can provide in some cases a significant enough source of energy to alter the cooling properties of the planet at a few Gyrs.

For tidal energy dissipation to significantly affect the contraction and thus the radius of the planet, however, tidal heat must be deposited deep in the convective layers. Turbulent viscosity (characteristic of what is usually referred to as "equilibrium tide") may lead to dissipation of heat at depth [194]. However, for the planets of interest, the convection turnover time exceeds the tidal period, so that convective dissipation is probably too slow to be efficient in short-period planets as well as in their host stars [195, 196]. Excited short wavelength g -modes (characteristic of "dynamical tides") at the interface between convective and radiative zones [197] would dissipate within the

radiative region, since g -modes do not propagate in isentropic regions, only affecting the outermost parts of irradiated planets. An interesting alternative mechanism in rapidly rotating planets might be short-wavelength, low-frequency inertial waves, restored by Coriolis rather than buoyancy forces, excited at the envelope-core boundary in the central parts of the planet. These waves can propagate and might dissipate in the convective inner regions and are thus more prone to affect the planet's structure than the aforementioned gravity modes [198, 199, 200]. In that case, the tidal quality factor is found to depend on the orbital period and core size as $Q' \propto R_c^{-5} P^2$ [200]. As discussed above after eqn.(7), the inferred age of the systems implies that Q'_* can not be substantially smaller than the nominal values $Q'_* \approx 10^5$ - 10^6 . The same holds true for Q'_p . Indeed, most of the transiting planets are predicted to have a core whose state remains uncertain (see §4.1.2). A solid core implies a much lower quality factor, $Q'_{core} \sim 10^2$ - 10^3 , than for a fluid or gaseous body, i.e. a more dissipative planetary interior, which in turn increases the expected tidal dissipation ($dE_{tide}/dt \propto 1/Q'_p$). The eccentricity of Io's orbit, however, implies that $6 \times 10^4 \lesssim Q_{Jup} \lesssim 2 \times 10^6$ [201]. Moreover, as mentioned above, if inertial waves are the main culprit for tidal energy dissipation, Q'_p is predicted to be of the order of $\sim 10^6$ for Jupiter (Io's orbital period is $P = 1.77$ d) and $\sim 10^7$ - 10^8 for hot Jupiters ($P \sim 3$ -4 d). This suggests that the jovian planet cores may have melted, under the action of the violent accretion episodes during the formation or of tidal heating during the evolution.

Besides the gravitational tides mentioned in this section, it is worth mentioning the possibility for short-period, strongly irradiated planets to experience *thermal tides* [202]. Thermal tides arise from the torque exerted by the stellar gravitational field on the thermal bulge produced in the planet's outer layers by the stellar time-dependent insolation. In that case, an equilibrium state in which gravitational and thermal tide effects balance each other can be reached, leading to asynchronous spin and/or possibly to finite eccentricity. This process, however, has been shown not to be valid in the case of gaseous bodies since, in the absence of a surface crust, the torque exerted on the thermal bulge vanishes [203].

8. Observational constraints

8.1. The radius anomaly of transiting exoplanets

As mentioned in §2.2 a significant fraction of transiting exoplanets exhibits abnormally large radii (see Fig. 2). This puzzling property is one of the most titillating observational discoveries in this new field and still requires a robust explanation. Several ideas have been proposed, as described below, but none of them has yet received a consensus.

8.1.1. Atmospheric circulation As mentioned in §6.3, close-in planets receive a substantial amount of energy from the star. The resulting heating of the outer planet layers affects the vertical temperature stratification and, consequently, the planet's

evolution and thus radius at a given age, as described in §6.3. This effect, however, is insufficient to explain observed radii $\gtrsim 1.2 R_{\text{Jup}}$. Irradiation can also modify the horizontal temperature profile. Indeed, if the planet is tidally locked and receives constantly the stellar flux on the same hemisphere, strong temperature contrasts can exist between the day- and night-sides of the planet, inducing rapid atmospheric circulation (see §5). The resulting fast winds may produce a heating mechanism in the deep interior of the planet, slowing down its evolution and yielding a larger than expected radius. This suggestion was based on numerical simulations of atmospheric circulation by [117], which produce a downward flux of kinetic energy of about $\sim 1\%$ of the absorbed stellar flux. This heat flux is supposed to dissipate in the deep interior, producing an extra source of energy during the planet's evolution. According to these simulations, this mechanism yields a typical heating rate of $10^{27} \text{ erg s}^{-1}$, which can explain the inflated radius of hot Jupiters like HD209458b ([204, 149]). The validity of this scenario, however, is still debated. The substantial transport of kinetic energy found in the simulations of [117] strongly depends on the details of atmospheric circulation models and has not been confirmed by other simulations ([118]). Although important efforts are devoted to the development of multi-D dynamical simulations of strongly irradiated atmospheres (see §5), the various simulations so far yield very different results ([127]). Furthermore, as demonstrated by [205], a proper description of the physical mechanisms responsible for energy dissipation and drag in the flow (*e.g.*, shocks, turbulence) is mandatory to obtain reliable descriptions of heat redistribution and wind speeds across irradiated exoplanetary atmospheres.

Assuming this mechanism is at play in all close-in planets, and arbitrarily adding an extra-source of energy corresponding to $0.5\% \times F_{\text{inc}}$, [150] find a correlation between the mass of heavy elements required to fit the transit radii and the metallicity of the parent star. This result, however, is highly speculative, since it crucially depends on the aforementioned assumption of a *constant* fraction of F_{inc} . If this wind-induced mechanism is at play in all close-in planets, one expects a correlation between the planet radius "excess", defined as the relative difference between the observed radius R_{obs} and the theoretical radius R_{th} obtained with regular irradiated models, $\frac{R_{\text{obs}} - R_{\text{th}}}{R_{\text{th}}}$, and the incident stellar flux F_{inc} , normalised to the planet's intrinsic flux $F_{\text{int}} = \frac{L_{\text{int}}}{4\pi R_{\text{th}}^2}$, with $L_{\text{int}} = \int -T \frac{dS}{dt} dm$, where S is the specific entropy of the irradiated planet. This relation is illustrated in Fig. 10 for a handful of transiting systems. Whether the expected trend exists or not is not clear, in particular when considering the fact that WASP-12's large radius may be explained by tidal heating, as mentioned in §8.1.2 below. Clearly, a more detailed analysis, extended to all transiting planets, is required to explore this issue.

To summarize, although atmospheric circulation remains an attractive possibility to explain the "hot-Jupiter" radius anomaly, a robust confirmation of this mechanism, in particular of heat transport at deep enough levels to affect the internal adiabat, is needed, based on more sophisticated numerical simulations. It should also be noted that planets far enough from their host star ($\gtrsim 0.1 \text{ AU}$) should not be affected by this mechanism, a diagnostic eventually testable with the Kepler mission.

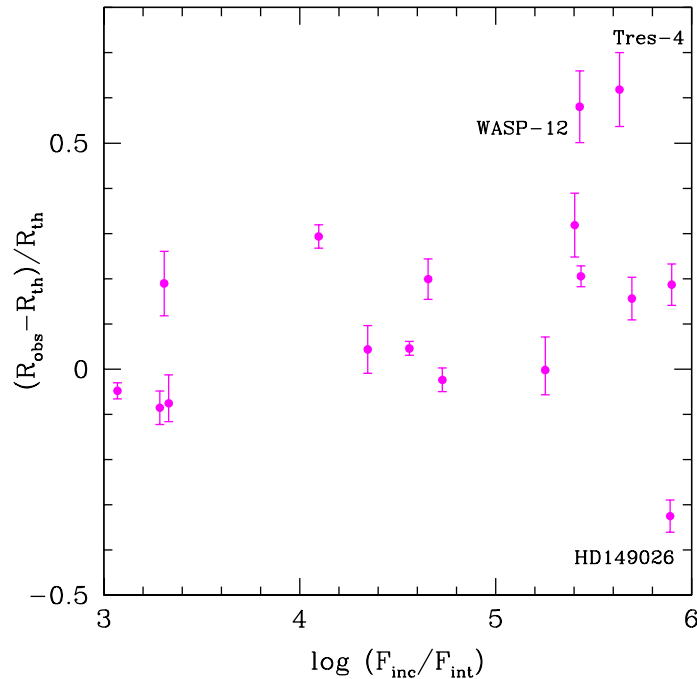


Figure 10 Radius excess of transiting exoplanets as a function of the incident stellar flux F_{inc} normalised to the planet's predicted intrinsic flux at the age of the system, $F_{\text{int}} = \frac{L_{\text{int}}}{4\pi R_{\text{th}}^2}$. The radius excess is defined as $\frac{R_{\text{obs}} - R_{\text{th}}}{R_{\text{th}}}$, where R_{obs} is the observed radius and R_{th} is the predicted radius of the planet at the age of the system. The error bars on the radius correspond to the quoted observational values.

8.1.2. Tidal effects Following [167], several studies have suggested tidal heating as a possible mechanism to explain inflated transiting planets (see §7.3). A heating rate of the order of 10^{27} erg s $^{-1}$, consistent with the tidal dissipation rate given in eqn.(13) and about 100 times the typical intrinsic energy flux of hot-Jupiters, dissipated in the planet's convective interior over appropriate timescales could in principle explain the observed abnormally large radii for at least some *coreless* planets. The presence of a central core yields a smaller radius and thus requires a larger energy rate. As discussed in §7.3, the first calculations ([167]) exploring the effect of tidal dissipation were based on incorrect tidal evolution timescales and assumed constant orbital properties over time. The correct impact of tidal dissipation on the planet radii from their supposed initial semi-major axis and eccentricity, taking into account the opposite effects of decreasing a and e on the tidal dissipation rate \dot{E} along the evolution (see eqn.(13)) has been explored only recently [186, 175, 176], although under some restrictive conditions (see second footnote in §7.2). In some cases, this heat source is found to be substantial at the age of the system, possibly affecting the planet's contraction and helping solving the radius discrepancies, *assuming tidal dissipation occurs deep in the convective interiors*

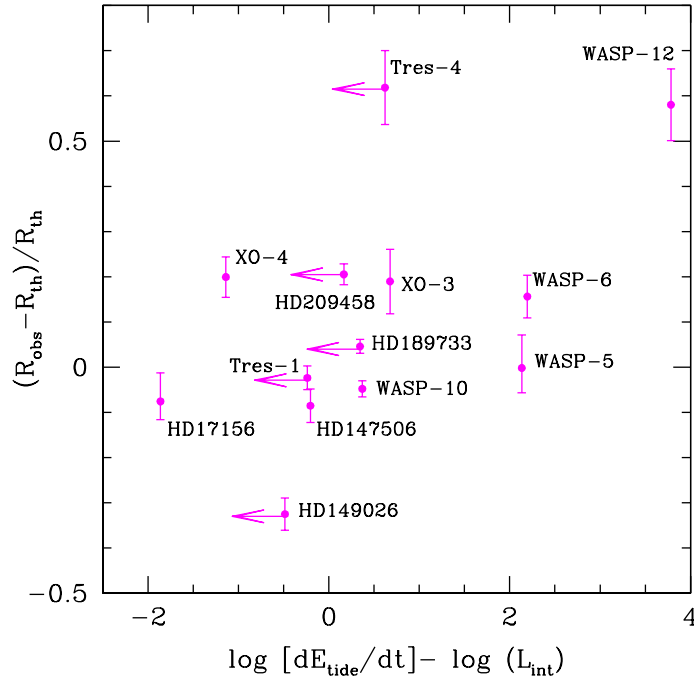


Figure 11 Radius excess (same definition as in Fig. 10) of transiting exoplanets as a function of the tidal dissipation contribution (see eqn.(13)), assuming constant values for a and e , at the age of the system. A value $Q'_p = 10^6$ is assumed for the planet's tidal quality factor. Objects shown with a left arrow have a (measured or assumed) eccentricity $e \leq 0.01$, and their tidal dissipation is calculated here assuming $e = 0.01$.

(see discussion in §7.3). As shown in Fig. 11, WASP-12 experiences extreme tidal heating, which may explain its strikingly large radius (see [176]). Tidal heating due to finite eccentricity, however, does not seem to be the lacking dominant mechanism responsible for *all* the observed abnormally large radii. Indeed, as illustrated in Fig.11 (see also [175, 176]), there is no obvious correlation between abnormally inflated planets and tidal dissipation energy. Tres-4, for instance, experiences a tidal heating comparable to its internal energy rate, even though being notably inflated (see [176]). However, proper calculations of the complete (not truncated at a given eccentricity order and including the rotational energy) tidal evolution equations remain to be done to fully address this issue.

An other source of tidal heating can arise if the orbit is inclined relative to the stellar quadrupole, so that the planet makes a vertical oscillation in the quadrupole field of the star once per orbit. This effect, however, has been shown to be utterly negligible [152]. Finally, as mentioned in §7.3, thermal tides can not be maintained in gaseous planets and thus can not provide an extra source of heat [203].

8.1.3. Atmospheric enhanced opacities A possibility to slow down the contraction of a self-gravitating body and to obtain a larger radius at a given age is to increase the atmospheric opacities. This solution was recently suggested by [151] to explain the puzzling large radii of some transiting planets. Alteration of atmospheric properties (chemistry, clouds, opacities) by strong optical and UV irradiation or enhanced atmospheric metallicities are suggested as the source of the increased opacities, although the authors do not work out the physical processes that could possibly lead to such an increase. In order to mimic the effect of enhanced opacities, they assume supersolar atmospheric metallicities (up to 10 times solar). The combined effects of enhanced opacities and of the presence of a dense core is found to reproduce the observed radius spread of transiting planets (see Fig. 2). Interestingly enough, [151] also finds the same correlation as suggested by [150] between planet core mass and stellar metallicity. Although enhancement of the atmospheric opacities of irradiated extrasolar planets is by no means excluded, given our limited knowledge of the various physical processes at play in such situations, the results obtained by [151], based on the increase of atmospheric metallicities, remain questionable. First of all, similar consistent calculations by [206] yield a *smaller* radius for the planet, as the larger mean molecular weight due to the increased metallicity counterbalances and even dominates the slower contraction due to the enhanced opacities. Second of all, although significant heavy element enrichment is observed in the atmosphere of our Solar System giant planets (see §2.1), convective transport in these (cool) planets is predicted to occur all the way up to the atmosphere, constantly bringing up heavy material to the atmospheric layers. Irradiated planet atmospheres are radiatively stable down to deep levels. To maintain heavy elements high up in these stably stratified outer layers requires a (yet to be worked out) efficient mechanism to counteract gravitational settling. More importantly, a stratification with heavy elements on top of a (lighter) H/He envelope, as done in [151] has been shown to be unstable, leading to "salt-fingers" instabilities [87]. The effect of strong irradiation, altering the chemistry and cloud properties requires additional work, as pointed out by the authors themselves [151]. Therefore, although enhanced atmospheric opacities in strongly irradiated planets is a possibility, it requires more robust physical foundations to be considered as the source of the abnormally large radii of irradiated planets. In any event, even such super-solar metallicity models cannot explain the most inflated transiting planets presently detected, like *Tres-4b* and *WASP-12*, implying the need for one or several alternative mechanisms ([151, 175]).

8.1.4. Reduced interior heat transport The idea of Stevenson that convection may not be as efficient as usually assumed in planetary interiors was resumed and applied to the case of exoplanets by [88]. These authors show that conditions prevailing in giant planet interiors could be favourable to the development of double-diffusive (layered) or oscillatory convection, if a molecular weight gradient is present (see 4.3). With characteristic Prandtl number (i.e. the ratio of kinematic viscosity over thermal diffusivity), $Pr \sim 10^{-2}$ -1, and inverse Lewis number, defined as the ratio of solute to

thermal diffusivity, $Le^{-1} \sim 10^{-2}$, conditions in planets are not too different from those found on Earth. Indeed, double-diffusive convection, characterised by the formation of multiple thin diffusive layers surrounded by (small-scale) convective regions, is a well known process in laboratory experiments, or in some parts of oceans and salty lakes, where the stabilizing gradient is due to salinity (the so-called thermohaline convection), with characteristic numbers $Pr = 7$ and $Le^{-1} = 10^{-2}$ for salty water [207]. The presence of a molecular weight gradient in the interior of giant planets could be inherited from the formation process, during the accretion of gas and planetesimals, or due to core erosion. Assuming a molecular weight gradient in the inner parts of a Jupiter-like planet, [88] show that if multiple layers can form, they might survive long enough to affect substantially the planet evolution. Heat transport by layered convection is indeed much less efficient than large-scale convection and the heat escape from the hot, deep parts of the planet is significantly reduced. The upshot is a larger planet at a given age than its homogeneous, adiabatic counterpart ([88]). Depending on the number of layers and the steepness of the molecular weight, the presence of this process could explain the observed spread in transit planet radii. If confirmed, this scenario would bear important consequences on our general understanding of planetary internal structure. High spatial resolution multi-dimensional numerical simulations, which are progressing at a remarkable pace, might be able in a foreseeable future to confirm or to reject the existence of layered or oscillatory convection under planetary conditions. Note that, according to this scenario, one should not expect any correlation between the radius and the incident flux, contrarily to other suggested mechanisms like the atmospheric circulation outlined in §8.1.1.

8.2. Brown dwarfs versus massive giant planets

As underlined in §1, brown dwarfs and planets overlap in mass. Observations of low mass stars and brown dwarfs in young clusters suggest a continuous mass function down to $\sim 6 M_{Jup}$, indicating that very low mass objects form as an extension of the star formation process [208]. There is indeed strong observational support for the brown dwarf formation process to be similar to the stellar one [209, 210], and analytical theories of star formation from the gravoturbulent collapse of a parent cloud do produce proto-brown dwarf cores in adequate numbers compared with the observationally determined mass spectrum [211, 212, 213]. In parallel, the discovery of "super" Jupiter-mass objects $> 10 M_{Jup}$ orbiting a central star (see Fig. 12) emphasizes the need for identification criteria enabling the distinction between a brown dwarf and a planet. Radii significantly smaller than predictions for solar or nearly-solar metallicity objects would reveal the presence of a significant amount of heavy material, an unambiguous signature of planetary formation process. The case of the 8 Jupiter mass transiting planet HAT-P-2b (or HD147506b, [214]) is interesting in this context, as its radius is consistent with the presence of a significant amount of heavy elements ($\gtrsim 10\%$ in mass fraction) and cannot be reproduced by a solar metallicity brown dwarf model ([216]),

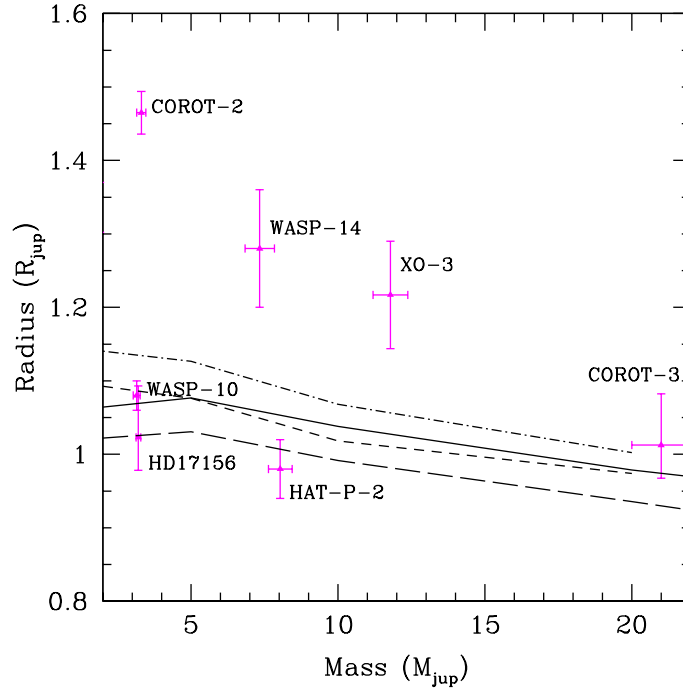


Figure 12 Mass-radius relationship for massive transiting exoplanets. The curves show theoretical predictions at 1 Gyr (models from [19, 216]). Solid line: solar metallicity without irradiation; long-dash: heavy element mass fraction $Z=10\%$ and without irradiation; dash-dot: solar metallicity and irradiation from a Sun at 0.05 AU; short-dash: heavy element mass fraction $Z=10\%$ with irradiation from a Sun at 0.05 AU. The name of objects in the overlapping mass regime between planets and brown dwarfs are indicated.

as illustrated in Fig. 12. If confirmed, HAT-P-2b might be the illustration that planets can form by core accretion up to a least 8 times the mass of Jupiter. The nature of CoRoT-Exo-3b, a $\sim 21 M_{\text{Jup}}$ object orbiting an F3V type star ([215]), however, remains ambiguous, given the present uncertainties on the radius determination ([216]). Enhanced metallicity is also expected to leave its mark on the atmospheric properties of a planet and may provide signatures of its formation process in a proto-planetary disk. However, abundance patterns in the cool atmospheres of planets and brown dwarfs may be severely affected by different complex processes (non-equilibrium chemistry, cloud formation, photochemistry, see §5). Predictions are thus uncertain and determination of clear spectral diagnostics requires much additional work before they can be used to distinguish a planet from a brown dwarf (see [28]).

8.3. Hot Neptunes and evaporation process

About twenty planets with masses less than $\sim 20 M_{\oplus}$ have been discovered by radial velocity surveys. Since these small planets are at the detection threshold, this number is relatively large, indicating that they should be rather common. Because of their low mass, their presence at close distance from their parent star raises the question about their origin. Observational evidences that close-in planets may undergo significant evaporation process ([217]) gave rise to the idea that hot-Neptunes may have formed from more massive progenitors and have lost a substantial amount of their gaseous envelope ([218]). This idea and the interpretation, in terms of evaporation, of the observations of [217] are currently controversial ([219]). Preliminary models of evaporation for hot-Jupiters induced by the stellar XUV radiation predicted large evaporation rates which could significantly affect the planet evolution ([220]). More recent theoretical works based on improved treatment of atmospheric escape now reach different conclusions and find much smaller rates than predicted just after the observations of [217] (see [221] and references therein). Small evaporation rates are also consistent with the observed mass function of exoplanets ([222]). Furthermore, formation models based on the core-accretion scenario can easily produce hot-Neptunes composed of a large core of heavy material without the accumulation of a substantial gaseous envelope ([223, 224, 225]). Their existence can thus be explained without the need to invoke strong evaporation processes. Getting the final word requires (i) more statistics in the low planetary mass regime, (ii) confirmation of the observations and interpretation of [217] and (iii) improved models of evaporation of close-in planets.

Independently of these issues, the interior properties of hot-Neptune planets were recently revealed by the discovery of GJ 436b ([226]) and HAT-P-11b ([227]), two transiting planets of $\sim 22 M_{\oplus}$ and $\sim 26 M_{\oplus}$, respectively. They are remarkably analogous to Uranus and Neptune, in terms of heavy material content, with a radius indicating heavy element enrichment greater than 85%. For GJ 436b, models with $\sim 20 M_{\oplus}$ core of ice or rock and a gaseous H/He envelope of $\sim 2 M_{\oplus}$ reproduce its observed radius ([19]). HAT-P-11b also appears to be a super-Neptune planet with $\sim 90\%$ heavy element and $\sim 10\%$ H/He envelope (see Fig. 14 of [227]). Given current uncertainties on the modelling of planetary interior structures, only their bulk composition can be inferred, and the total amount of heavy material, its composition and distribution within the planet cannot be accurately determined. As mentioned in §4.1.2 and shown in [19], the thermal contribution of heavy elements to the cooling of Neptune-like planets significantly affects their evolution and thus radius at a given age. The discovery of GJ436b and HAT-P-11b confirms the large heavy element content that can be expected in planets, comforting our general understanding of planet formation through the core accretion model. However, since there is no obvious signature of an evaporation process on the structure of a planet, current observations cannot certify whether or not these hot-Neptunes have undergone strong evaporation episodes during their evolution.

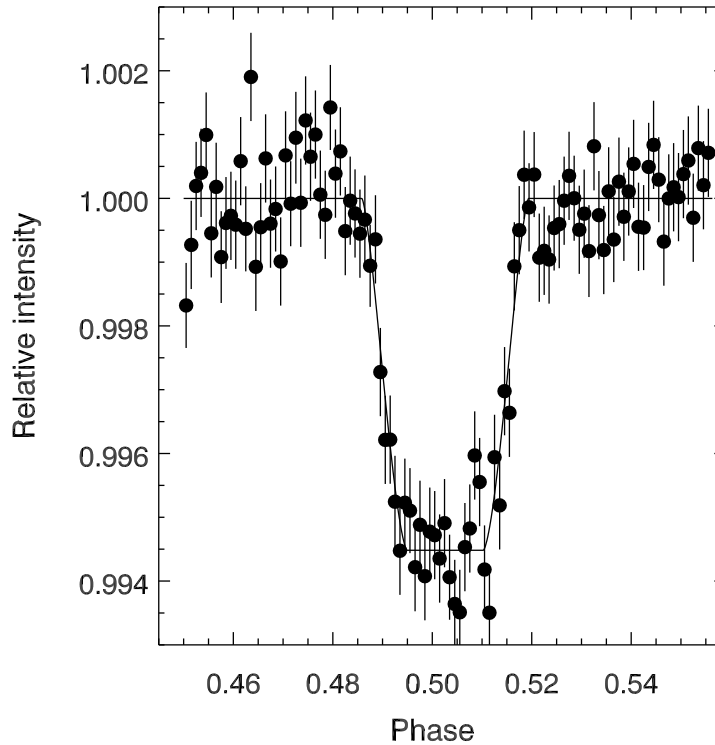


Figure 13 Secondary eclipse photometry of HD 189733 at $16\ \mu\text{m}$, as measured by the IRS instrument on board *Spitzer* [228].

8.4. Light of extra-solar planets

So far, exoplanets have only been discovered by indirect techniques, without actually direct photon detection from the planet. Various claimed direct detections cannot unambiguously assess the very nature of the observed object, brown dwarf or planet. The recent detections of the $3\text{-}M_{\text{Jup}}$ planet Fomalhaut-b [56] and of the young (30 to 160 Myr old) triple system orbiting HR 8799 [229], however, represent exciting discoveries and, if coplanarity of the system is clearly demonstrated for the second case, might indeed be the first genuine direct detections of exoplanets. Somewhat counter intuitively, the short period hot-Jupiters were the first class of exoplanets to have their atmospheric properties measured, both photometrically and spectroscopically; a major contribution made possible with the *Spitzer Space Telescope* [230, 231]. The majority of *Spitzer* exoplanet observations target transiting EGPs orbiting nearby stars. As a transiting planet disappears behind its star, there is an observable drop in the total flux from the system as the planet's contribution is temporarily absent. This event is often called the secondary eclipse, and the depth of the eclipse is a direct measure of the planet-star flux ratio (e.g. Fig 13). The orbital phase coverage of these *Spitzer* data confine them to measuring the temperature and chemistry of a planet's day side only. Since the

planet-star flux ratio is the quantity measured, secondary eclipses depths increase with increasing wavelength roughly in accordance with the Rayleigh-Jeans approximation, resulting in deep eclipse amplitudes even at wavelengths where the planet flux is quite small. Figure 14 compares the full set of secondary eclipse flux measurements for HD189733b to dayside model spectra with uniform global redistribution of absorbed stellar flux ($\alpha = 0.25$) and dayside-only redistribution ($\alpha = 0.5$). In this example, there is a transition between 2 and 3 μm from one case to the other, suggesting depth-dependent energy redistribution, probably caused by horizontal flows over a narrow range of pressures [104].

The anticipated diversity in hot-Jupiters is beginning to emerge from secondary eclipse observations with hints that some hot-jupiters have temperature inversions across their photospheres (HD209458b and TrES-4) while others may not (HD189733b). Temperature inversions can be produced by a variety of processes, for example, the presence of a high-atmosphere opacity source could produce strong heating at low pressures. Plausible opacity sources could be the molecules TiO and VO which can play an important role in shaping the atmospheric structures [232, 233]. However it has yet to be

shown that an identifiable opacity source can produce a temperature inversion deep (high pressure) enough to reach the photosphere and impact the IR fluxes. Alternatively, strong horizontal currents could cool deeper layers while leaving layers above still quite hot resulting in a fairly deep inversion [124, 104]. The exact nature of the inversion and its cause will require observations of higher precision and across a broader range of hot-Jupiters. *Spitzer* flux measurements have also started to identify those planets that have strong or weak day-to-night redistribution of absorbed stellar energy leading to cold or warm night side temperatures. Observations covering a large fraction of an orbital period can provide potential maps of the atmospheric temperatures allowing tests of global circulation models [234, 235]. In one example, HD189733b, the hottest location of the atmosphere (measured at 8 μm) is actually not located at the substellar point but instead leads the sub-stellar point by 2 to 3 hrs (i.e. down wind by 20 to 60°) – as roughly predicted by global circulation models [122]. For a more comprehensive review of *Spitzer* exoplanet observations see [236].

Ground-based secondary eclipse observations at K- and L-bands are being attempted by several groups and, so far, only upper limits have been obtained [241, 242, 243, 237]. These near-IR flux upper limits, however, can be extremely useful for estimating the level of day-to-night redistribution since, in many cases, the peak of the energy distribution for hot-exoplanets is actually in the near-IR, rather than at wavelengths covered by *Spitzer*. As demonstrated by [104] the question of redistribution is fundamentally a bolometric argument and measuring the fluxes at multiple band passes including shorter wavelengths is critical for determining the true day-to-night flux redistribution.

As a transiting planet passes between Earth and the host star, the wavelength-dependent opacities in the planet’s atmosphere obscure stellar light at different planet

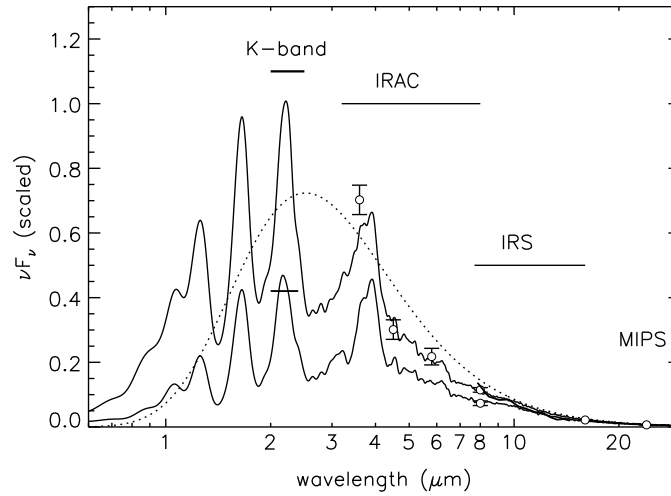


Figure 14 HD189733b energy distributions assuming full-redistribution (lower line, $\alpha = 0.25$) and no-redistribution (top line, $\alpha = 0.5$) along with a 1450K blackbody spectrum (dotted line). Over plotted are IR ground and space-based flux measurements for HD189733b [237, 238, 228, 239]. The lower point at 8 μm is the night side flux measurement from [240].

radii, leading to a primary transit eclipse with a wavelength-dependent amplitude. Spectroscopic observations during primary transit (called transit spectroscopy) can measure planet radii across various absorption features from which atomic and molecular mole fractions can be inferred. There have been a number of models for EGP transmission spectra [244, 245, 246, 247, 248, 249, 250], all using 1-D plane-parallel or spherically symmetric geometry and a single 1-D temperature-pressure profile to represent the depth-dependent (radial) structure. The broad Na and K doublets in the optical were predicted to produce large radius variations [244]. Subsequent observations using the STIS instrument on board HST detected the Na doublet ([251]), though it was much weaker than predicted, prompting speculations about high clouds and photoionization [247, 248]. Following the Na detection, an extended hydrogen atmosphere surrounding HD209458b was discovered using transit spectroscopy in the UV at Lyman- α [217]. At Lyman- α wavelengths, HD209458b is ~ 3 times larger than at optical wavelengths. The extended atmosphere may also contain carbon and oxygen as reported by [252]. Strong water absorption (Fig. 15) was identified in the HD 209458b STIS data [250] and later in emission on the dayside with secondary eclipse Spitzer observations [253]. A marginal detection of water in HD189733 b was made with Spitzer [254] in the IR and later detected at much higher confidence (along with methane) with NICMOS on board HST [255]. Ground-based observations have also successfully repeated the Na detection in HD209458 b [256], and have actually resolved the doublet into its two components for HD189733 b [257].

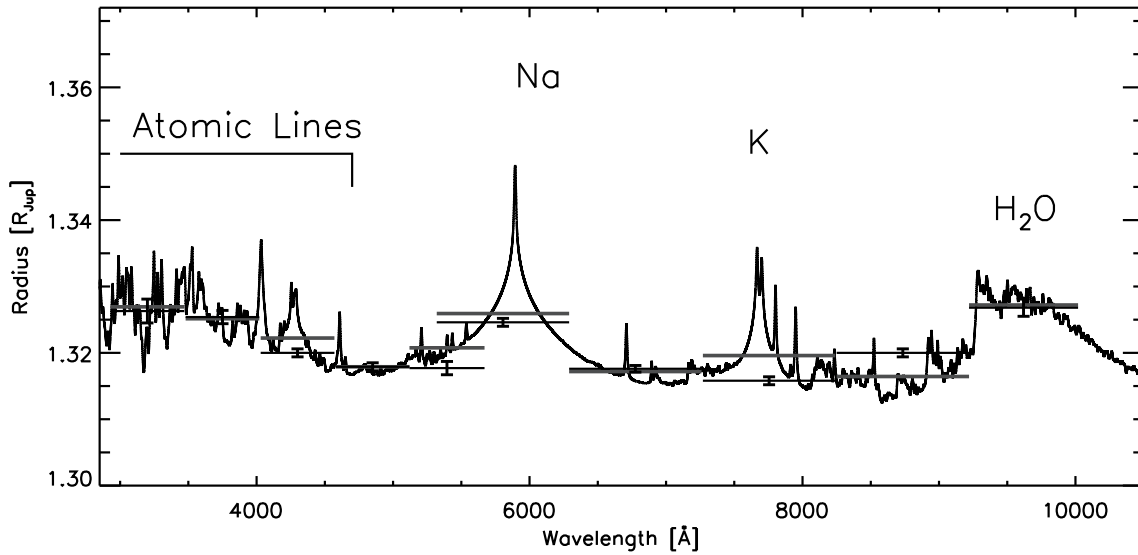


Figure 15 Model monochromatic transit radii for HD209458b. Horizontal bars correspond to mean radii across bins with λ -ranges indicated by the width of each bar. Observations are shown with $1\text{-}\sigma$ error-bars [240, 250].

Higher up in the atmosphere, at lower pressures and densities, global circulation patterns become inefficient at redistributing heat and the temperatures are likely close to their radiative equilibrium values. Under radiative equilibrium, there will be significant horizontal temperature variations caused by different incident angles of incoming radiation from the host star. Furthermore, the photoionization of species like sodium and potassium has been shown to be very important for modelling the transmitted spectrum [248, 250]. Given the transparency of the upper limb, photoionization (and potentially more complicated photochemistry) may also spill over to the night side. Consequently, *independent of the global circulation*, there will be horizontal structure that is not likely well reproduced in a 1D model of the transmitted spectrum. Efforts to model this region in 3 dimensions are underway and should greatly improve our ability to use transit spectroscopy to infer upper-atmospheric properties of hot-Jupiters.

9. The future

The next decades promise a wealth of discoveries and new knowledge in the field of exoplanets. Our understanding of exoplanet properties will progress with expected developments on experimental and theoretical fronts. Ongoing and future high-pressure experiments in various national laboratories (Livermore and Sandia in the US, LIL and Laser Mega-Joule laser projects in France) and advancements of first principle N-body numerical methods (DFT, path-integral, quantum molecular dynamics) promise substantial progress on EOS in the critical pressure regime of 0.1-10 Mbar, characteristic

of H and He pressure ionization, and at temperatures typical of planetary interiors. The question of internal heat transport, and its efficiency in the presence of molecular weight gradients, may receive an answer from current progress in high-resolution multi-D numerical simulations. Numerical tools, such as the one developed by [258] and devoted to high resolution stellar radiative hydrodynamical simulations, using grid refinement methods and high-order spatial schemes, offer promising techniques to handle this problem. The future study of exoplanet atmospheres is also poised for great progress in the coming years. Coupled multi-D radiation hydrodynamical simulations are in the works, and new and improved opacity databases are emerging. Our understanding of clouds and chemistry (much of which comes from studying brown dwarf atmospheres) is steadily improving.

From the observational standpoint, a multitude of missions based on different techniques and wavelengths will provide a wealth of data. The combination of all these techniques defines efficient strategies for the detection and characterization of exoplanets, as highlighted by the impressive prospective work by [259]. Current and future space-based surveys, like CoRoT and Kepler, will significantly increase the number of known transiting systems. These two space missions may soon answer to the question whether Earth analogs, in terms of mass and size, exist in the Habitable Zone. A large number of additional transiting planets will also emerge in the next years from ongoing ground-based wide-field surveys as HATnet, TrES or WASP. Increasing the number of detections will allow a more comprehensive study of exoplanet physical properties (mass-radius relationship, bulk composition, abnormal radii, etc..) and will confirm (or not) current observed trends, placing them on firmer statistical footing. CoRoT is expected to find many tens of transiting giant planets and could discover a few tens (10-40) of super-Earths. CoRoT recently announced the detection of the very first transiting super-Earth candidate (still to be confirmed at the time of this writing), CoRoT-Exo-7b, with a radius of $1.7 R_{\text{Earth}}$ ([260]). The Kepler mission, launched in March 2009, will observe hundreds of thousands of stars for transiting events and is expected to find about 1000 transiting gas giants. This mission will certainly provide the most reliable way to get a census of Earth-sized planets around solar type stars. It is capable of detecting several hundreds super-Earth in all orbits up to 1 year and more than 50 Earth-sized planets ($1 R_{\oplus}$) in all orbits, with about a dozen in ~ 1 -year period orbits ([82, 76, 261]). Kepler will thus be able to discover a large number of planets, but only a sub-sample of the most suitable ones will be followed-up with Doppler velocimetry from the ground (HARPS-NEF and possible future instruments). [76] estimate that Kepler, limited only by available observing time for HARPS-NEF, could obtain, for dozens of super-Earths, their radius and mass with a precision of less than 5% and 10% respectively. Such an accuracy allows bulk estimates of the composition for planets in the mass range $1\text{-}10 M_{\oplus}$ [76]. More details on observational uncertainties for both CoRoT and Kepler can be found in [261].

Also, Kepler and CoRoT promise optical phase curves of short-period planets, while a refurbished Hubble Space Telescope will bring new transmission spectra (from the UV

to near-IR) and near-IR phase curves. Future missions like JWST and SOFIA also promise new and exciting exoplanet atmosphere observations. As the successor of HST and Spitzer, JWST will open new avenues in transiting exoplanet science with the characterization of intermediate and low mass exoplanets ($\leq M_{\text{Nep}}$). Currently, about ten hot Jupiters have been observed with Spitzer, allowing the analysis of their emergent spectra, and the Warm mission should double the number of detection [262]. Spitzer could in principle detect hot super-Earths in favorable cases, and JWST will extend these detections to "warm super-Earths" ($\sim 300\text{K}$). The latter mission is also capable of measuring the day-night temperature difference of warm Earth-like planets orbiting M-dwarfs, just as done by Spitzer for several hot Jupiters [262]. JWST should be able to obtain light curves of primary and secondary eclipses of 1 R_{\oplus} terrestrial planet around main sequence stars with a high precision, allowing basic characterisation of the transiting exoplanet and the possibility to search for unseen planets [263].

From the ground, the recent discovery of the triple planetary-mass system orbiting HR 8799 [229] has clearly demonstrated the potential of ground-based direct imaging campaigns. The development of a new generation of adaptive-optics (AO) systems, such as VLT-SPHERE or the Gemini Planet Imager (GPI) augurs well for direct imaging of planets orbiting solar type stars, enabling direct detection of hundreds of warm Jovian planets in the next decade ([264]). These systems, which are precursors for the next generation of extremely large telescopes with apertures around 30m, attempt to reach in a near future contrasts up to 10^8 , allowing the detection of young Jupiters of less than 100 Myr around solar type stars ([265]). In the next years, AO coronagraphs should thus be sensitive to a broad range of self-luminous giant planets in the ranges 1-10 M_{Jup} , 4-40 AU and 10-10 000 Myr ([264]). High contrast imaging systems on Extremely Large telescopes (ELT) should achieve contrasts allowing the characterisation of any self-luminous planet at high signal-to-noise ratio (SNR) and spectral resolution. Even mature planets in the inner part of solar systems (< 2 AU) should become detectable through reflected light ([264]).

Better characterization of our own solar system planets is also crucial to carry on, with for instance the Juno mission to Jupiter which should measure atmospheric abundances, in particular water, and accurately map its gravitational and magnetic fields. As stressed in this review, the understanding of exoplanet physical properties is strongly linked to the understanding of their formation process. On this front, our knowledge will greatly improve with the possibility to detect recently formed giant planets either directly, through their thermal or accretion luminosity using AO techniques as above mentioned, or indirectly by imaging the structures (*e.g* gaps) they should produce in their disks with projects such as ALMA.

Finally, the possibility of identifying habitable planets, with the detection of water vapor and signs of chemical disequilibrium in their atmospheres, is given by projects such as DARWIN/TPF and JWST. This could be one of the most significant and stimulating achievements of Science, as it may tell us that we are not alone in the universe.

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